

AD-A128 723

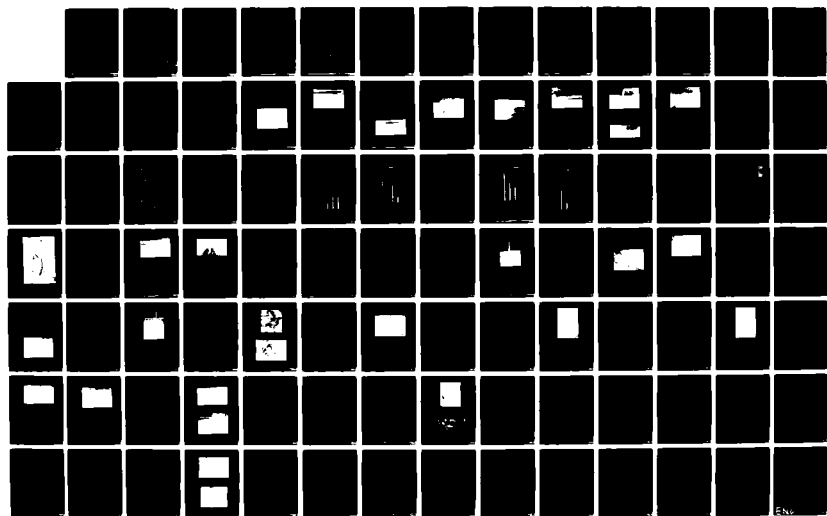
SHORE STABILIZATION WITH SALT MARSH VEGETATION(U)
COASTAL ENGINEERING RESEARCH CENTER FORT BELVOIR VA
P L KNUTSON ET AL. JAN 83 CERC-SR-9

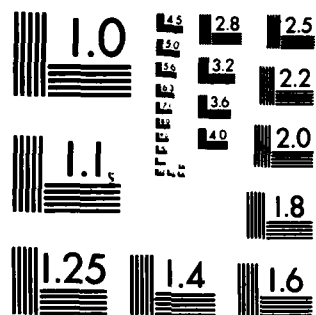
1/1

UNCLASSIFIED

F/G 13/2

NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

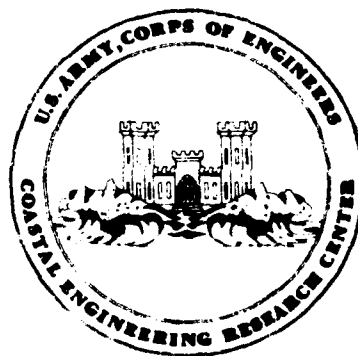
Shore Stabilization with Salt Marsh Vegetation

by

Paul L. Knutson and W. W. Woodhouse, Jr.

SPECIAL REPORT NO. 9

JANUARY 1983



Approved for public release;
distribution unlimited.

U.S. ARMY, CORPS OF ENGINEERS
COASTAL ENGINEERING
RESEARCH CENTER

Kingman Building
Fort Belvoir, Va. 22060

AD A 128 723

DTIC FILE COPY

DTIC
ELECTE
MAY 25 1983

E

Reprint or republication of any of this material shall give appropriate credit to the U.S. Army, Corps of Engineers.

U.S. Army Coastal Engineering Research Center
Kingman Building
Fort Belvoir, Virginia 22060

Contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SR-9	2. GOVT ACCESSION NO. A128 723	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SHORE STABILIZATION WITH SALT MARSH VEGETATION		5. TYPE OF REPORT & PERIOD COVERED Special Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Paul L. Knutson W.W. Woodhouse, Jr.		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of the Army Coastal Engineering Research Center (CERRE-CE) Kingman Building, Fort Belvoir, VA 22060		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS D31234
11. CONTROLLING OFFICE NAME AND ADDRESS Department of the Army Coastal Engineering Research Center Kingman Building, Fort Belvoir, VA 22060		12. REPORT DATE January 1983
		13. NUMBER OF PAGES 95
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Marsh vegetation Shore stabilization Erosion control		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report is published to provide engineers and scientists with guidelines on using coastal marsh vegetation as a shore erosion control measure in coastal regions of the United States. This erosion control alternative is suitable for relatively sheltered shorelines such as those found on bays, sounds, and estuaries. For various reasons this alternative has not been found to be effective in the Great Lakes, Alaska, or Hawaii. Criteria are provided on (1) determining site suitability, (2) selecting plant materials, (3) planting procedures and specifications, (4) estimating project costs, and (5) assessing impact.		

DD FORM 1 JAN 73 1473

EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

PREFACE

This report is published to provide engineers and scientists with guidelines on the use of salt marsh vegetation as a shore erosion control measure in coastal regions of the United States.

This is one of a series of reports to be published to form a Coastal Engineering Manual (CEM). The report is based, in part, upon information presented in SR-4 "Building Salt Marshes Along the Coasts of the Continental United States" (Woodhouse, 1979). The work was carried out under the U.S. Army Coastal Engineering Research Center's (CERC) Development of Functional and Structural Design Criteria work unit, Coastal Structure Evaluation and Design Program, Coastal Engineering Area of Civil Works Research and Development.

The report was prepared by P.L. Knutson, Ecologist, Coastal Ecology Branch, CERC, and W.W. Woodhouse, Jr., Professor Emeritus of Soil Science, North Carolina State University, under the general supervision of E.J. Pullen, Chief, Coastal Ecology Branch, and Mr. R.P. Savage, Chief, Research Division, CERC. R.A. Jachowski, former Chief, Coastal Design Criteria Branch, Engineering Development Division, was the CEM project monitor.

The authors express appreciation to S.W. Broome and E.D. Seneca for their review and comments.

Technical Director of CERC was Dr. Robert W. Whalin, P.E.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

Accession For	
NTIS GRA&I	<input checked="checked" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A	



Ted E. Bishop
TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

CONTENTS

	Page
CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI).....	10
GLOSSARY.....	11
I INTRODUCTION.....	13
II BACKGROUND.....	13
1. Role of Marshes in Shore Stabilization.....	13
a. Wave Attenuation and Sediment Trapping.....	13
b. Soil Reinforcement.....	15
2. Coastal Salt Marshes of the United States.....	15
a. Eastern Region Marshes.....	17
b. Western Region Marshes.....	19
3. Establishing Coastal Marshes for Shore Stabilization.....	20
a. Invasion and Recovery in Natural Marshes.....	20
b. Planting to Encourage Establishment.....	21
c. Research on Planting to Control Erosion.....	22
III EVALUATING SITE SUITABILITY.....	25
1. Factors Influencing Planting Success.....	25
a. Soils.....	25
(1) Type.....	25
(2) Salinity.....	26
(3) Oxygen-Aeration.....	27
b. Exposure to Direct Sunlight.....	28
c. Shore Width Available for Planting.....	28
d. Sediment Supply.....	30
e. Summary.....	30
(1) Soil Type.....	30
(2) Salinity.....	30
(3) Oxygen-Aeration.....	30
(4) Exposure to Direct Sunlight.....	30
(5) Shore Width Available for Planting.....	30
(6) Sediment Supply.....	30
2. Evaluating Wave Climate Severity.....	31
a. Fetch.....	31
b. Shore Configuration.....	31
c. Sediment grain size.....	34
d. Winds.....	34
e. Ship-Generated waves.....	34
f. Offshore Depth.....	34
g. Tidal Currents.....	37
h. Discussion.....	37
i. Summary.....	37
IV SELECTING PLANT SPECIES, PLANT MATERIALS, AND PLANTING TECHNIQUES...	38
1. Selecting Plant Species.....	38
a. Principal Species.....	38
b. Other Useful Species.....	38
2. Selecting Plant Materials.....	40
3. Selecting Planting Techniques.....	42

CONTENTS--Continued

	Page
4. Summary.....	43
a. Principal Erosion Control Species.....	43
b. Plant Materials.....	44
c. Planting Methods.....	44
V FERTILIZATION REQUIREMENTS.....	44
1. Types of Fertilizer.....	45
2. Placement of Fertilizer.....	46
3. Fertilizer Rates.....	46
4. Maintenance Fertilizer.....	47
5. Summary.....	48
a. Types of Fertilizers.....	48
b. Placement.....	48
c. Rate.....	48
d. Maintenance.....	48
VI PLANTING SPECIFICATIONS FOR PRINCIPAL SPECIES.....	48
1. Smooth Cordgrass (<i>Spartina alterniflora</i>), Atlantic and Gulf Coasts.....	48
a. Planting Techniques.....	50
(1) Sprigs.....	50
(2) Pot-Grown Nursery Seedlings.....	51
(3) Plugs.....	53
b. Soils and Salinity.....	53
c. Planting Zone.....	53
d. Planting Density.....	54
e. Planting Width.....	54
f. Planting Date.....	54
g. Fertilization Requirements.....	55
h. Planting Maintenance.....	55
i. Summary.....	56
2. Pacific Cordgrass (<i>Spartina foliosa</i>), Southern Pacific Coast..	56
a. Planting Techniques.....	58
(1) Sprigs.....	58
(2) Pot-Grown Nursery Seedlings.....	58
(3) Plugs.....	60
b. Soils and Salinity.....	61
c. Planting Zone.....	61
d. Planting Density.....	62
e. Planting Width.....	62
f. Planting Date.....	62
g. Fertilisation Requirements.....	62
h. Planting Maintenance.....	63
i. Summary.....	63
3. Pacific Northwest.....	63
a. Lyngbye's Sedge (<i>Carex lyngbyei</i>).....	63
(1) Planting Techniques.....	65
(2) Soils and Salinity.....	65
(3) Planting Zone.....	65
(4) Planting Density.....	65
(5) Planting Width.....	65
(6) Planting Date.....	65

CONTENTS--Continued

	Page
(7) Fertilization Requirements.....	65
(8) Planting Maintenance.....	65
(9) Summary.....	66
b. Tufted Hairgrass (<i>Deschampsia caespitosa</i>).....	66
(1) Planting Techniques.....	66
(2) Soils and Salinity.....	66
(3) Planting Zone.....	66
(4) Planting Density.....	66
(5) Planting Width.....	66
(6) Planting Date.....	66
(7) Fertilization Requirements.....	66
(8) Planting Maintenance.....	68
(9) Summary.....	68
VII PLANTING SPECIFICATION FOR OTHER USEFUL SPECIES.....	68
1. Black Needle Rush (<i>Juncus roemerianus</i>).....	68
a. Planting Techniques.....	69
b. Soil and Salinity.....	69
c. Planting Zone.....	69
d. Planting Density.....	69
e. Planting Width.....	69
f. Planting Date.....	69
g. Fertilization Requirements.....	69
2. Common Reed (<i>Phragmites communis</i>).....	69
a. Planting Techniques.....	70
b. Soil and Salinity.....	70
c. Planting Zone.....	70
d. Planting Density.....	70
e. Planting Width.....	70
f. Planting Date.....	70
g. Fertilization Requirements.....	70
3. Cordgrasses.....	71
a. Big Cordgrass (<i>Spartina cynosuroides</i>).....	71
b. Saltmeadow Cordgrass (<i>Spartina patens</i>).....	71
(1) Planting Techniques.....	71
(2) Soils.....	74
(3) Planting Zones.....	74
(4) Planting Density.....	74
(5) Planting Width.....	74
(6) Planting Date.....	74
(7) Planting Management.....	74
(8) Summary.....	75
c. Gulf Cordgrass (<i>Spartina spartinas</i>).....	75
4. Red Mangrove (<i>Rhizophora mangle</i>), Black Mangrove (<i>Avicennia</i> <i>germinans</i>), and White Mangrove (<i>Laguncularia racemosa</i>).....	75
a. Planting Techniques.....	78
b. Salinity.....	78
c. Planting Zone.....	78
d. Planting Density.....	78
e. Planting Width.....	78
f. Planting Date.....	78

CONTENTS--Continued

	Page
g. Fertilization Requirements.....	78
h. Planting Management.....	78
5. Saltgrass (<i>Distichlis spicata</i>).....	79
6. Seaside Arrowgrass (<i>Triglochin maritima</i>).....	79
7. Siltgrass (<i>Paspalum vaginatum</i>).....	79
VIII COST.....	79
1. Cost Comparison with Other Erosion Control Methods.....	79
2. Planting Costs.....	81
a. Site Preparation.....	81
(1) Grading the Beach Face.....	81
(2) Wave-Stilling Devices.....	81
b. Harvesting, Processing, and Planting.....	81
c. Site Maintenance.....	83
(1) Fertilizer.....	83
(2) Debris Removal.....	83
(3) Wildlife Predation.....	83
3. Summary	83
a. Cost Comparison.....	83
b. Planting Costs.....	83
IX IMPACT ASSESSMENT.....	84
1. Potential Benefits.....	84
a. Marsh Ecology.....	84
b. Nutrient Cycling.....	85
c. Esthetics.....	85
2. Potential Negative Impacts.....	85
a. Public Access.....	85
b. Heavy Metal Release.....	85
c. Introducing Nuisance Species.....	87
d. Nutrient Pollution.....	87
3. Summary.....	88
a. Potential Benefits.....	88
b. Potential Negative Impact.....	88
LITERATURE CITED.....	89

TABLES

1 Wave heights produced by three vessels.....	37
2 Smooth cordgrass survival in lower intertidal areas.....	54
3 Pacific cordgrass survival in lower intertidal zone.....	62
4 Man-hours required to harvest, process, and plant 1,000 planting units.....	82

FIGURES

1 Coastal regions of the United States.....	16
---	----

CONTENTS

FIGURES—Continued

	Page
2 Smooth cordgrass marsh (Virginia).....	17
3 Upper zone of saltmeadow cordgrass and lower zone of smooth cordgrass (Maine).....	18
4 Pacific cordgrass marsh (San Francisco, California).....	19
5 Lyngbye's sedge marsh (Oregon).....	20
6 Scarp of bank on seaward edge of an eroding coastal marsh (San Francisco Bay, California).....	21
7 Oldest reported salt marsh planting in the United States (Virginia)...	22
8 Establishment period for Cedar Island, North Carolina.....	23
9 Stability period for Cedar Island, North Carolina.....	23
10 Erosion period for Cedar Island, North Carolina.....	24
11 Clearing woody vegetation to provide direct sunlight exposure.....	29
12 Planting performance versus longest fetch.....	32
13 Planting performance versus average fetch.....	33
14 Planting performance versus shoreline configuration.....	35
15 Planting performance versus sediment grain size.....	36
16 Vegetative Stabilization Site Evaluation Form.....	39
17 Typical smooth cordgrass transplant or "sprig" from the wild or from an intertidal nursery.....	41
18 Planting by hand.....	43
19 Mechanical planting with disk-type tobacco planter.....	44
20 Smooth cordgrass.....	49
21 Pot-grown nursery seedlings.....	51
22 Harvesting seed.....	52
23 Nylon rope fence around smooth cordgrass planting.....	55
24 Pacific cordgrass.....	57
25 Pot-grown nursery seedlings.....	59

CONTENTS

FIGURES--Continued

	Page
26 Harvesting Pacific cordgrass seed.....	59
27 Cordgrass-mussel plugs of Pacific cordgrass.....	61
28 Lyngbye's sedge.....	64
29 Tufted hairgrass.....	67
30 Seven years growth from single sprig of black needle rush, CERC Field Research Facility, Duck, North Carolina.....	69
31 Erosion control planting with common reed, CERC Field Research Facility, Duck, North Carolina.....	70
32 Saltmeadow cordgrass meadow (Maine).....	72
33 Saltmeadow cordgrass planted landward of smooth cordgrass.....	72
34 Gulf cordgrass.....	76
35 White, black, and red mangroves.....	76
36 Cost comparison of various shore stabilization methods.....	80
37 Vegetative erosion control project (Maryland).....	86
38 Erosion control structure (Maryland).....	86

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins ¹

¹To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9) (F - 32)$.

To obtain Kelvin (K) readings, use formula: $K = (5/9) (F - 32) + 273.15$.

GLOSSARY

ERGOT - A dark, spongy, parasitic mass of fungus found on the ovaries of various grasses.

FETCH LENGTH - The horizontal distance wind blows over open water to generate waves.

IRREGULARLY FLOODED - Areas of the shoreline which are not covered and uncovered by the rise and fall of the tide on a daily basis, but are subject to flooding during extreme lunar tides or wind setup. Generally, the region between mean high water and the estimated highest tide.

PRIMARY PRODUCTIVITY - The rate at which energy is stored by photosynthesizing organisms (chiefly green plants) in the form of organic substances.

PLANT PROPAGATION - Increase in number, or multiplication, of plants to perpetuate the species or variety. Also, the process and methods employed by man to promote natural increase in some plants and to bring increase about under conditions when it would not otherwise take place.

PLUG - A root-soil mass with attached aerial stems of living plants. A type of PROPAGULE.

POTTED NURSERY SEEDLINGS - Plants raised in nurseries in peat moss or plastic pots, usually the latter. Seeds are placed in the pots, germinated, and plants are raised for 3 to 7 months. A type of PROPAGULE.

PROPAGULE - A plant material such as seeds, SPRIGS, or seedlings used in PLANT PROPAGATION.

RHIZOME - A horizontal underground stem.

REGULARLY FLOODED - Areas of the shoreline which are usually covered and uncovered by the daily rise and fall of the tide. Generally, the region between mean low water and mean high water.

SPRIG - A part of a plant consisting of at least one node (joint of a stem from which the leaves arise) with attached stems and roots of living plants. A type of PROPAGULE.

SHORE STABILIZATION WITH SALT MARSH VEGETATION

by
Paul L. Knutson and W.W. Woodhouse, Jr.

I. INTRODUCTION

Shore erosion is a common problem in the bays, sounds, and estuaries of the coastal United States. A wide variety of structures have been developed and used to control this erosion. However, due to environmental objections and economic limitations it is often impractical to use even the most innovative of these structures. This is particularly true for relatively low wave energy areas where erosion may be costly but is not yet catastrophic. Low-cost, nonstructural techniques are now available for controlling erosion in salt and brackish water, low wave energy areas of the contiguous United States using native marsh plants. Vegetation, where feasible, is usually lower in cost than structures and may be more effective.

This report provides comprehensive guidelines on the use of marsh plants to control shore erosion resulting from wind waves and tidal currents. The report has been carefully organized to facilitate its use as a reference document. Each major section addresses a specific facet of project planning, design, or construction; most sections end with a summary of information generally presented in the form of graphs, tables, and matrices.

II. BACKGROUND

This section provides a background of information on the subject of using marsh plants to control shore erosion. It discusses the role of marshes in providing stability to the shore, describes natural coastal marshes by region, and provides an introduction to the concept of encouraging marsh establishment to reduce shore erosion.

1. Role of Marshes in Shore Stabilization.

Marsh plants perform two functions in abating erosion. First, their aerial parts form a flexible mass which dissipates wave energy. As wave energy is diminished, both the offshore transport and the longshore transport of sediment are reduced. Optimally, dense stands of marsh vegetation can create a depositional environment, causing accretion rather than erosion of the shoreface. Second, many marsh plants form dense root-rhizome mats which add stability to the shore sediment. This protective mat is of particular importance during severe winter storms when the aerial stems provide only limited resistance to the impact of waves.

a. Wave Attenuation and Sediment Trapping. Wave attenuation in marshes has not been studied extensively. Wayne (1975) measured small waves passing through a smooth cordgrass marsh at Adams Beach, Florida. Dean (1979) gives the following empirical methodology for describing wave dampening in marshes, based on empirical estimates of the fluid drag forces occurring on vertical cylinders and laboratory observation of various arrays of cylinders:

It can be shown that with reasonable assumptions, the ratio of incident wave height H_1 , seaward of a stand of marsh grass, and height H_{le} , landward of the stand of marsh grass, are related as follows:

$$\frac{H_{le}}{H_1} = \frac{1}{1 + AH_1}$$

where

$$A = \frac{C_D D l}{3\pi S^2 d}$$

C_D = Drag coefficient (≈ 1.0)

D = grass stalk diameter

l = length of "stand" through which waves propagate

S = average spacing of grass stalks (assumed on square centers)

d = water depth (assumed to be constant)

Example: Consider the following: grass stalks 4 millimeters in diameter on a 6-centimeter spacing in a water depth of 25 centimeters extending over a stand length, l , of 10 meters. For this example an incident wave height, H_1 , of 15 centimeters will be considered. The height, H_{le} , at the landward end of the stand is

$$A = \frac{C_D D l}{3\pi S^2 d}$$

$$A = \frac{1(0.4)1000}{3\pi(6)^2 25}$$

$$A = 0.0471$$

and

$$H_{le} = \frac{H_1}{1 + AH_1}$$

$$H_{le} = \frac{15}{1 + 0.0471(15)}$$

$$H_{le} = 8.8 \text{ cm}$$

This is a 41-percent reduction in the incident wave height. The associated rate at which energy will be dissipated against the shoreline will be reduced by 65 percent. In a series of field experiments Knutson, Seelig, and Inskeep (in preparation, 1983) found a modified version of the Dean model useful in predicting wave damping in sloping, natural marshes. They found that under conditions similar to those used in the above example about 64 percent of the energy associated with a 15-centimeter wave was dissipated by only 2.5 meters of natural, sloping marsh.

As the wave energy impacting the shore is reduced, there is increased potential for sediment deposition and decreased potential for erosion. Woodhouse, Seneca, and Broome (1974) measured sediment deposition resulting from marsh plantings and reported the deposition of 15 to 30 centimeters of sediment along three planted profiles at Snow's Cut, North Carolina, during a 30-month period.

The influence marshes have on waves depends primarily on the width of the marsh ("l" in Dean's equation). The width to which a marsh can extend, under optimal conditions, depends on the geographical area in which the marsh is located and the tidal amplitude and slope of the shoreline. The density of plants within a particular marsh depends on many variables including (1) species, (2) geographical area, (3) elevation zone within the marsh, (4) season, (5) substrate, (6) maturity of the marsh, (7) salinity, and (8) wave climate.

b. Soil Reinforcement. Though it is empirically evident that plant root systems improve soil stability, there is little experimental evidence on this subject. Gray (1974) summarized findings concerning soil reinforcement with vegetation. He noted that some independent studies have shown that plant roots do significantly increase soil stability (Endo and Tsuruta, 1969; Manbeian, 1973). In these studies the shear strength of vegetated soils was as much as two and three times greater. In addition, the shear strength of soils was higher when the volume fraction or weight density of the root system was greater.

2. Coastal Salt Marshes of the United States.

A coastal marsh is an herbaceous (plants lacking woody stems) plant community found on the part of the shoreline which is periodically flooded by salt or brackish water. A number of species in the grass family (*Poaceae*), sedge family (*Cyperaceae*), and rush family (*Juncaceae*) commonly form coastal marshes.

Coastal marshes occur naturally in the intertidal zone of moderate- to low-energy shorelines along tidal rivers and in bays and estuaries. These marshes may be narrow fringes along steep shorelines, but can extend over wide areas in shallow, gently sloping bays and estuaries. Such lands were extensive and widely distributed along the Atlantic, peninsular Florida, gulf, and Pacific coasts of the United States before development by man (Fig. 1).

There are two major groups of coastal salt marshes in the United States, based on physiographic differences—marshes of the Atlantic, peninsular Florida, and gulf coasts (the eastern region) and those characteristic of the northern and southern Pacific coasts (the western region). The eastern

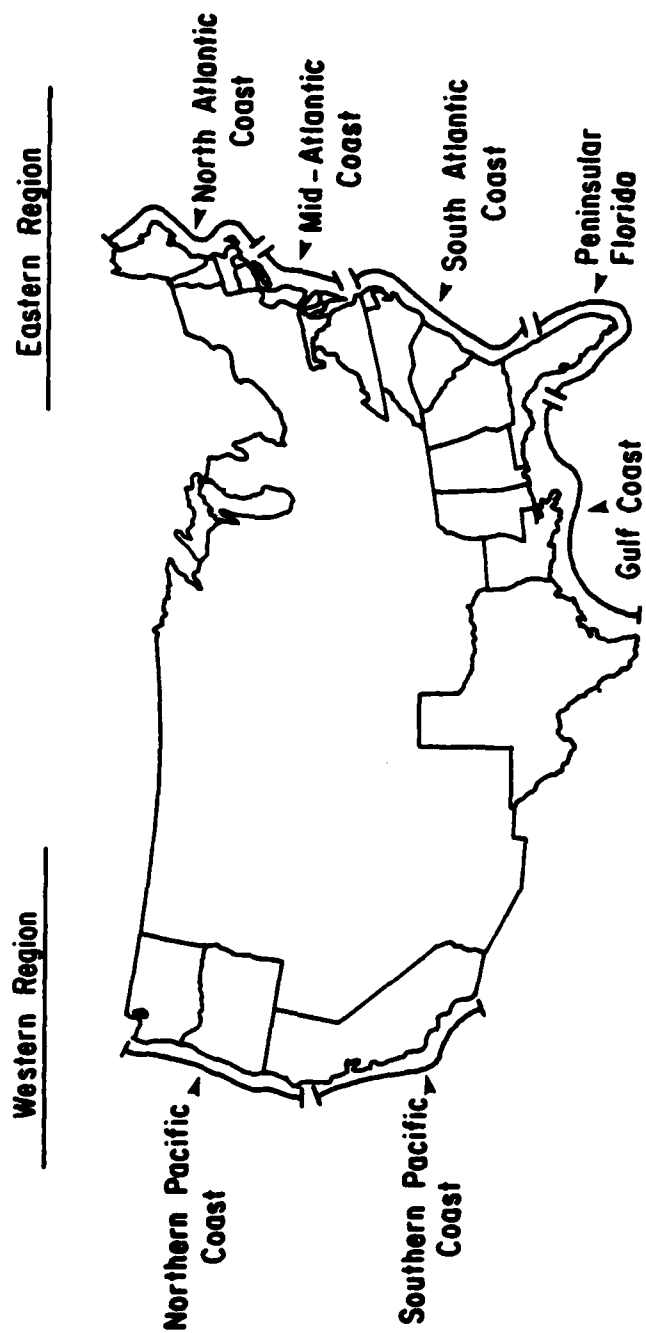


Figure 1. Coastal regions of the United States.

marshes usually form on a gently sloping coast with a broad continental shelf, under conditions of a sea slowly rising relative to the land. Western marshes are mostly formed in relatively narrow river mouths which drain almost directly onto a steeply sloping continental shelf along a slowly emerging coastline (Cooper, 1969). Consequently, the western estuaries and their marshes are more limited in development than those of the east and tend to mature more rapidly.

There are two types of coastal salt marshes: the regularly flooded low marsh, which is considered to be the most valuable and usually the most essential to erosion control, and the irregularly flooded high marsh.

a. Eastern Region Marshes. Vegetation of eastern region marshes is remarkably uniform. The intertidal zone from New England to Texas is dominated by a single species, smooth cordgrass (*Spartina alterniflora*) (Fig. 2). Two grasses, saltmeadow cordgrass (*S. patens*) and saltgrass (*Distichlis spicata*), usually dominate the zone immediately above high tide along these coasts with two rushes on slightly higher sites--black-grass (*Juncus gerardi*) north of the Virginia Capes and black needle rush (*J. roemerianus*) southward.



Figure 2. Smooth cordgrass marsh (Virginia).

Eastern marshes divide into four general areas: north Atlantic, mid-Atlantic, south Atlantic, and gulf. Typical north Atlantic marshes occur on fibrous or silty peat because the shore is predominantly composed of hard rock. The intertidal zone of pure stands of smooth cordgrass is usually relatively narrow with a well-developed upper zone of saltmeadow cordgrass mixed with saltgrass (Fig. 3). Saltmeadow cordgrass often occupies a larger area than smooth cordgrass. Pure stands of black-grass in the higher parts of the zone often form a fringe at the edges of the marsh.



Figure 3. Upper zone of saltmeadow cordgrass (foreground) and lower zone of smooth cordgrass (background) (Maine).

Marshes in the mid-Atlantic region undergo subtle changes from the north Atlantic type on Long Island to the south Atlantic type at the Virginia Capes. To the north there are relatively limited areas of smooth cordgrass with the greatest area covered by saltmeadow cordgrass. Localized high salinity patches are dominated by pickleweed (*Salicornia* spp.). Big cordgrass (*Spartina cynosuroides*) and several rushes (*Scirpus* spp.) occur along creeks and tidal stream mouths where the freshwater influence is greater. Black needle rush increases in importance near the mouth of the Chesapeake Bay. The tall form of smooth cordgrass appears along creek banks.

South of the Chesapeake Bay, the south Atlantic marshes typically form behind barrier beaches and in estuaries where rivers deposit heavy silt burdens. Smooth cordgrass occupies vast areas of mostly soft sediments between mean sea level (MSL) and mean high water (MHW). Large areas of high marsh, primarily black needle rush, occur where astronomical tides are restricted and wind setup predominates, e.g., in Pamlico Sound, North Carolina. South of Daytona Beach, Florida, (peninsular Florida), the typical south Atlantic marshes are largely replaced by mangrove trees that form the tropical and subtropical equivalent of salt marshes. Marshes of the south Atlantic type occur on the gulf coast with the largest expanses on the Mississippi River delta. Smooth cordgrass occupies the areas regularly flooded by saltwater with a brackish marsh of saltmeadow cordgrass, big cordgrass, saltgrass, and black needle rush covering vast areas. Gulf cordgrass (*Spartina spartinae*) replaces saltmeadow cordgrass above MHW on fine-textured soils along the coasts of Texas and southwestern Louisiana. Hypersaline conditions in the Laguna Madre (Corpus Christi to Brownsville, Texas), due to limited rainfall and high temperatures, largely exclude coastal marshes from the south Texas

coast. Black mangroves (*Avicennia germinans*) occasionally appear southward of Galveston and on offshore islands farther north.

b. Western Region Marshes. Marsh vegetation in the western region is less uniform than in the east. The vast majority of western marshes are found in scattered bays and lagoons and in the mouths of some tributaries. The coastal marshes of the southern Pacific are very distinct from those in the northern Pacific. Along the southern Pacific, seasonally high levels of salinity in coastal estuaries greatly limit the diversity of intertidal vegetation. In parts of the larger bays such as the San Francisco Bay, salinity concentrations reach or exceed sea strength during the dry summer months when evaporation exceeds rainfall runoff and tidal exchange. Smaller tributaries periodically run dry allowing seawater to intrude upstream. Under these conditions Pacific cordgrass (*Spartina foliosa*), the western region equivalent of smooth cordgrass, is the dominant flowering plant of the regularly flooded part of the intertidal zone (Fig. 4). Only in the reaches of tributaries where freshwater is a consistent influence is cordgrass displaced by other species such as Alkali bulrush (*Scirpus robustus*). Broad reaches of the irregularly flooded high marsh are dominated by pickleweed, a plant widely distributed but of little importance on the east coast. The stresses of salinity in the high marsh are even more severe than in regularly flooded marshes. The pickleweed's ability to tolerate salinity concentrations of more than twice sea strength provides this species with a formidable advantage over most other species. Saltgrass is common but seldom a dominant high marsh species.



Figure 4. Pacific cordgrass marsh (San Francisco, California).

Freshwater is a much greater influence on the marshes of the northern Pacific. In some areas such as the Olympic Peninsula of Washington, annual precipitation is more than 250 centimeters. The specific composition of these

marshes is more diverse than that on other coasts of the United States and elevation zones are less discrete. There is no single species such as Pacific cordgrass colonizing and dominating the lowermost, regularly flooded zone of this region. The regularly flooded low marshes are characterized by Lyngbye's sedge (*Carex lyngbyei*), tufted hairgrass (*Deschampsia caespitosa*), spike rushes (*Eleocharis* spp.), pickleweed, three-square bulrush (*Scirpus californicus*), Baltic rush (*Juncus balticus*), and seaside arrowgrass (*Triglochin maritima*) (Fig. 5). As in the southern Pacific, saltgrass is common in the high marsh but seldom dominant.



Figure 5. Lyngbye's sedge marsh (Oregon) (photo courtesy of D.L. Higley and R.L. Holton).

3. Establishing Coastal Marshes for Shore Stabilization.

a. Invasion and Recovery in Natural Marshes. In established stands of salt marsh, reproduction is principally vegetative; i.e., new plants arise from the horizontal runners of parent plants. Within these marshes, new growth is sheltered from wave activity by the surrounding vegetation. On unvegetated shores, marsh plants may be established by seed or from fragments of plant material dislodged from existing marshes. During establishment on bare sediments, unsheltered plants are vulnerable to wave attack and mortality is likely to be high. It is this vulnerability to wave attack during the early stages of establishment that prevents the natural invasion of marsh plants along much of the shoreline. Natural invasion only occurs in very sheltered areas or in relatively exposed areas where plant introduction happens to coincide with an extended period of low wave activity and an absence of severe storms. Even in mature marshes stems are continually broken off by wave action but new shoots arise to replace those lost. Stem density may be greatly reduced during storms while during periods of relative calm, the density may increase considerably. However, severe storms may cause permanent damage

to even mature marshes. Breaking waves may erode the vulnerable leading edge of the marsh forming a scarp or bank. In addition, long-term sea level rise and land subsidence may drown the seawardmost plants in the marsh, further reducing the stability of this zone. Once a scarp is established it is subject to continued erosion and the plants behind it can no longer spread seaward. This is particularly critical in sediment-poor situations where sediment accumulation cannot keep pace with subsidence and the marsh edges do not recover and rebuild between storms. Most coastal marshes show evidence of erosion because of these processes (Fig. 6). Once destroyed, the marsh will not reestablish until the events which led to its origin (the presence of plant fragments or seed and an absence of waves) are repeated.



Figure 6. Scarp or bank on seaward edge of an eroding coastal marsh (San Francisco Bay, California).

b. Planting to Encourage Establishment. With the use of agricultural techniques, plants can often be established on shorelines where natural processes of invasion have failed to produce plant cover. Marshes established in this manner may greatly improve the shore's stability and resistance to erosion. This erosion control alternative has been used successfully for many years in the United States. In the winter of 1928, a property owner on the eastern shore of Chesapeake Bay planted smooth cordgrass along more than 1 kilometer of shoreline in an attempt to reduce erosion. This shoreline has remained stable for more than 50 years and is the oldest reported example of shore stabilization with salt marsh vegetation in the United States (Knutson, et al., 1981) (Fig. 7). Similarly in 1946, a landowner on the Rappahannock River in Virginia graded an eroding shoreline and planted several varieties of salt-tolerant plants. This planting has prevented erosion for more than 30 years (Phillips and Eastman, 1959; Sharp and Vaden, 1970; Sharp, Belcher, and Oyler, 1981).



Figure 7. Oldest reported salt marsh planting in the United States (Virginia).

Most shoreline plantings do not have the longevity of these two examples. Planted marshes proceed through a cycle which includes periods of establishment, stability, and erosion, just as natural marshes do. The length of time required for a planting to complete this cycle is its "functional life" (the period over which it has functioned to reduce erosion). The life of a planting is influenced by the severity of wave conditions which impinge upon the shore. Areas subject to more severe wave conditions require longer to establish and have a shorter functional life. For example, Woodhouse, Seneca, and Broome (1974) discuss a shoreline planting at Cedar Island, North Carolina. This shoreline is subject to waves generated over a fetch of more than 20 kilometers. Because of these conditions, it would be anticipated that the period of establishment for a planting would be relatively long and the period of stability would be relatively short. The shore was planted in the spring of 1973. After one growing season (Fig. 8) the plant cover was incomplete and ineffective. However, by the end of the second growing season (Fig. 9), the shoreline was well vegetated and stable. By 1980 (Fig. 10), much of the planting had eroded away and the shoreline had returned to its preplanting condition. Therefore, the functional life of the planting at the site was about 6 to 8 years. Because erosion control plantings are made in difficult environments where nature has failed to establish plant cover, the functional life of plantings may be shorter than the life of typical natural marsh. However, this fact should not discourage the use of this alternative. Many costly shore protection structures function successfully for only 5 to 10 years.

c. Research on Planting to Control Erosion. In the late 1960's a major research program was initiated on stabilizing dredged material with marsh vegetation by scientists from North Carolina State University at Raleigh (Woodhouse, Seneca, and Broom, 1972, 1974). These studies on establishing

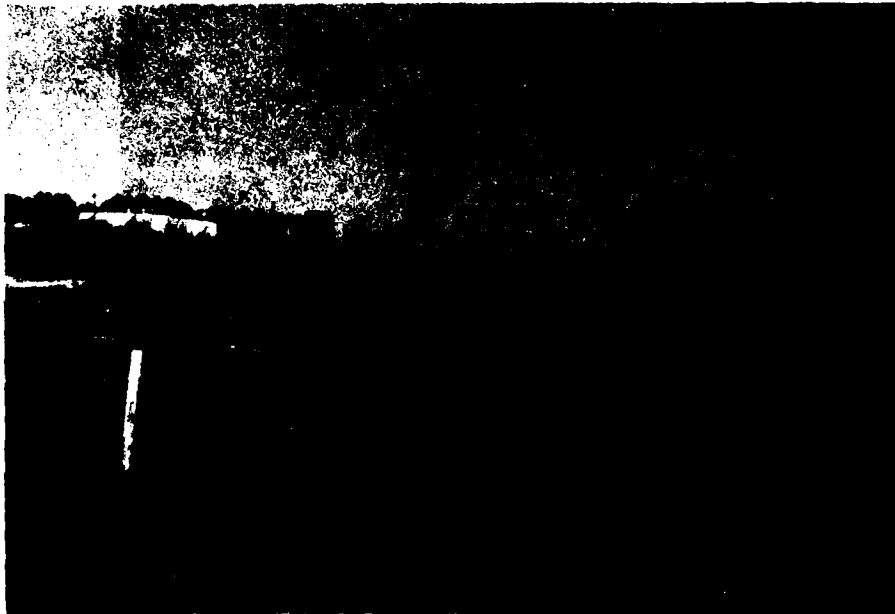


Figure 8. Establishment period for Cedar Island, North Carolina (10 months after planting).



Figure 9. Stability period for Cedar Island, North Carolina (17 months after planting).



Figure 10. Erosion period for Cedar Island, North Carolina (8 years after planting).

salt marsh plants on bare substrates provided valuable experience which was applied later to the subject of shore erosion control with vegetation (Woodhouse, Seneca, and Broome, 1976).

Researchers in other coastal regions have found that shoreline stabilization with plants can be successful--Garbisch, Woller, and McCallum (1975) in Chesapeake Bay; Webb and Dodd (1978) in Galveston Bay, Texas; Newcombe, et al. (1979) in San Francisco Bay, California. Based on these studies, design criteria for vegetation stabilization projects were developed (Knutson 1976, 1977a.). The U.S. Army Engineer Waterways Experiment Station (1978) conducted a nationwide study program on salt marsh establishment on dredged material in the mid-1970's resulting in design criteria for this use of vegetation.

Hall and Ludwig (1975) evaluated the potential use of marsh plants for erosion control in the Great Lakes. They concluded that there were few areas suitable for this method of shore protection because there are few sheltered shorelines. Marsh plantings are also subject to winter icing conditions and fluctuating lake levels in this region. However, vegetation can be used to stabilize upland areas. The roots of terrestrial plants add stability to the soil, retard seepage, and reduce surface runoff (Great Lakes Basin Commission, 1978; Gray, 1974, 1975; Dai, Hill, and Smith, 1977). Information on surface erosion and various techniques for its control (dewatering, slope grading, and planting ground cover species) are available from the Soil Conservation Service or County Agriculture Extension Agents.

In Alaska, a relatively short growing season, broad tidal ranges, high energy conditions, and icing prevent the use of salt marsh vegetation for erosion control. This alternative has not been used in the limited bays and estuaries of Hawaii.

III. EVALUATING SITE SUITABILITY

1. Factors Influencing Planting Success.

A number of factors are known to influence planting success. The following is a state-of-the-art discussion of these factors.

a. Soils.

(1) Type. A few salt marsh species are confined to certain soil types or conditions. Gulf cordgrass, for example, occurs almost exclusively on soils high in clay or underlain by clay at shallow depths. However, most other salt marsh plants exhibit a wide tolerance of substrates. They may be found growing on mineral soils ranging from coarse sands to heavy clays and on peats and mucks of widely varying nutrient content and degree of decomposition. This does not mean that soils are unimportant to marsh establishment and growth. Soil characteristics affect marsh planting in at least three respects--substrate stability, nutrient supply, and ease of planting.

Even under the most favorable conditions, transplants require several weeks to anchor themselves and still more time to develop an appreciable protective effect. Substrate is important to this process. Consequently, planting in loose sands is a poor risk if the site is likely to be subjected to high wave activity during the establishment period. Even when net erosion may be minimal, substrate movement or wave action may dislodge the transplants before they can become fully anchored. The threat of substrate movement is less critical in cohesive soils which tend to be more stable.

A limited nutrient supply is much more common to plantings on eroding shorelines than to plantings in sheltered areas or on dredged materials. Also, unlike other plantings, nutrient deficiencies on eroding shorelines are not necessarily confined to the more sandy materials. Soil materials exposed by erosion will usually be representative of subsoils of the adjacent uplands. These are often the highly weathered soils which are low in nutrients. Some of the most acute deficiencies, particularly of phosphorus, may occur on compact, cohesive soils (Broome, Seneca, and Woodhouse, in preparation, 1983). Further, the mechanics of correcting nutrient deficiencies become more complicated in compact soils. While the method of fertilizer placement is usually not critical on sands, it may make the difference between success and failure on clays or packed sandy loams (Broome, Seneca, and Woodhouse, in preparation, 1983).

Nutrient supply in organic soils is highly variable. Some peats are extremely deficient and as a consequence are very difficult to sustain plant growth; others are very well supplied with nutrients and are excellent mediums for marsh growth. The nature and origin of the soils in a region will often provide general guidance as to the probability of fertilizer needs. For example, young soils formed from moderately weathered materials, such as occur in the Mississippi Delta, are much less likely to be deficient in nutrients than the much older, highly weathered sediments that predominate along much of the Atlantic coast.

Soil characteristics can be of vital importance because of their influence on the marsh planting process, particularly on eroding shorelines. It is

essential that the soil be taken into account early as it will often dictate the planting method and thus have a major effect on costs. Loose, sandy soils are usually easy to plant; planting holes are readily opened by hand with shovels, spades, or dibbles and are easily closed and firmed after transplanting. Tractor-drawn planters work well on these soils and have a relatively low power requirement.

More compact, cohesive soils provide a more stable substrate for marsh planting than the loose sands, but the planting process itself may be more difficult. Cohesive or very compact sandy soils are usually stiff and resist the opening of holes or furrows and the proper closing and firming after planting. Planting openings in some fibrous peats are especially difficult to close satisfactorily. The power requirements of tractor-drawn planters on some compact soils are high enough to make this method impractical. Also, the opening of planting holes by hand on such soils will be very laborous and may become cost prohibitive. The power-driven auger is about the only practical solution for this problem on the more difficult soils. The importance of careful consideration of soil characteristics early in the planning process can scarcely be overemphasized.

(2) Salinity. Salinity is the one common factor that affects all salt marsh plants. These plants must have some salt tolerance, a prime requirement in this habitat. Some of the more tolerant species have the capacity to excrete salt through special structures (salt glands) in their leaves. A number of them possess another mechanism in their roots for screening toxic ions and slowing their inward penetration (Waisel, 1972). Plants of the regularly flooded, low marshes, such as smooth cordgrass, Pacific cordgrass, and the mangroves, are well equipped to live and grow in salinities up to 35 parts per thousand (sea strength). However, these plants are usually quicker to establish and more productive in salinities below sea strength. Seeds and young seedlings are usually more sensitive to salt concentration than are established plants.

Relatively little work has been done on salinity regimes of marsh soils and their effect on plants under field conditions. Soil salinity is not easy to investigate because of the high variability, in time and space, of salt concentrations. The concentration of salt required to eliminate a particular species from a site need not occur often or persist for more than a few hours or days. Consequently, these events may elude fairly intensive sampling.

Toxic concentrations usually do not develop in sandy marsh soils within the regularly flooded zone. The salinity in such soils tends to remain close to that of the surrounding water. However, this may not always be true of fine-textured soils in which salt may accumulate through ion exclusion by roots (Smart and Barko, 1978). Salt accumulation in the fine-textured marsh soils is probably held to a minimum by the drainage normally provided by root channels and animal burrows.

Salt damage may occur on newly planted areas due to concentration through evaporation in the zone between neap tide high water and spring tide high water during periods of low rainfall and warm temperatures following spring tides. This also occurs in sounds and bays subject to a wind setup with the wind pattern resulting in extended periods of low water during hot weather, as in Core Sound, North Carolina. Under these conditions, soil-water salinities

of 50 to 75 parts per thousand may develop and persist until diluted by rainfall or tidal inundation (Woodhouse, Seneca, and Broome, 1974).

Irregularly flooded high marshes are subject to occasional salt buildup through evaporation and ion exclusion regardless of soil texture. However, this is usually limited to poorly drained areas that are flooded by storm surges. In humid climates precipitation, plus freshwater seepage from higher ground, tends to keep salinities in most high marshes well below sea strength. Under more arid conditions, salt concentrations often exclude marsh species altogether.

In general, suitable plants which can be established in salinities up to about sea strength may be found in all coastal areas. Vegetative stabilization in bays and estuaries, where salinities seasonally exceed sea strength, is not likely to succeed. If salinity is a suspected problem, the presence, abundance, and vitality of native intertidal plants in sheltered areas near the proposed project will be an indicator of probable success.

(3) Oxygen-Aeration. From a practical marsh-building point of view, the scarcity of oxygen in marsh soils appears to be unimportant. There is no evidence that it prevents the establishment of marsh plants on sites that are otherwise suitable. Marsh soils are, by nature, chronically or periodically flooded and are, therefore, usually poorly to very poorly aerated. The severity and duration of this varies with such factors as topographic position, soil texture, and water regime, as well as the biological activity in the soil. Oxygen is supplied to these soils by water and the oxygen-bearing plants growing on them. Parts of intertidal marsh soils may be drained and aerated at each ebbside if the internal drainage allows appreciable emptying of pores during these brief intervals of exposure. Similarly, parts of high marsh soils become aerated during periods of dry weather and low water tables.

Most sediments, such as freshly deposited dredged materials, will be highly anaerobic or low in oxygen. However, this does not prevent the establishment of adapted marsh species. These plants have various adaptations to an anaerobic environment. For example, certain intertidal species have anatomical features that enable their leaves to supply oxygen to their roots (Teal and Kanwisher, 1966; Anderson, 1974; Kasapligil, 1976). Smooth cordgrass and probably many other grasses utilize ammonia, which is the usual form of nitrogen under anaerobic conditions, more efficiently than the nitrate form usually preferred by upland species (Gosselink, 1970; Woodhouse, Seneca, and Broome, 1976; Mendelssohn, 1979).

Some intertidal species contribute to the aeration of soils by releasing oxygen from their roots. This has been demonstrated for Pacific cordgrass under controlled conditions and in the field (Pride and Lingle, 1976; Wong, 1976), and has been frequently observed in the form of oxidized (yellowish or brown) zones around the roots and rhizomes of smooth cordgrass. Oxygen supplied in this way promotes the activity of other organisms and eventually contributes to improved internal drainage and increased aeration. Anaerobic conditions affect the growth of marsh plants by favoring the maintenance of nitrogen in the ammonia form and promoting the availability of such elements as iron and manganese by maintaining them in a reduced form. There probably are detrimental effects but little is known about them. Iron toxicity may occur because of the excessive availability of this element under highly

anaerobic conditions. Similar effects may occur with other elements or compounds but these are not known to limit marsh creation.

b. Exposure to Direct Sunlight. Tidal submergence greatly reduces the amount of light which can reach intertidal plants. Therefore, marsh plants rely heavily upon uninterrupted light exposure for photosynthetic activity during low water periods. Typically, the grasses, sedges, and rushes which form the intertidal marsh community are exposed to direct sunlight, because this zone lacks an overstory of either shrubs or trees.

In general, woody vegetation is not found within the intertidal zone of the coastal United States. The major exception to this is the occurrence of red mangroves (*Rhizophora mangle*) in southern Florida. On the Atlantic and gulf coasts, marsh-elder (*Iva frutescens*) grows on the outer margin of salt marshes. This plant grows closer to the marsh than any other woody species and is appropriately referred to as the "high tide bush." On the Pacific coast, frankenia (*Frankenia grandifolia*) is the first shrubby species encountered at the edge of the marshes. These and other shrubs form the transition between the marsh and the maritime forest.

Erosion patterns may alter the normal zonation of plant communities on the shore. Progressive erosion may have obliterated the marsh and shrub transition zones leaving a mature forest overhanging an exposed bank. Such a condition will preclude the establishment of emergent vegetation for erosion control because of its impact on the availability of light. In peninsular Florida, the introduced Australian Pine (*Casuarina equisetifolia*) often induces erosion along steep shorelines by shading out the native intertidal plants. If the area meets other criteria for erosion control with vegetation, however, the area can be planted if the overstory is completely cleared above the planting area and to a distance of at least 3 to 5 meters landward (Fig. 11). Continued control of overstorying species will be an essential part of the maintenance of such sites.

c. Shore Width Available for Planting. The width of the beach at an elevation suitable for plant establishment will determine the relative effectiveness of the erosion control planting. Waves are dampened as they pass through stands of marsh vegetation. The amount of dampening that occurs is directly related to the width of the marsh. From a survey of erosion control plantings, Knutson, et al. (1981) concluded that a practical minimum planting width is about 6.0 meters. If the potential planting area is not sufficiently wide, the shore must be graded to extend the planting area. Grading must be done far enough in advance of planting to allow for a consolidation of the disturbed soil to take place. Otherwise, transplants may be dislodged by the first minor storm before sufficient anchoring roots develop.

Though there is some variation in the elevation (tidal) zones in which marsh plants can be established, there are regional trends which are useful as a general guide. On the Atlantic and gulf coasts marsh plants can be found throughout much of the intertidal zone where the tidal amplitude is less than about 2.0 meters. Where the tidal amplitude exceeds 2.0 meters, the lower limit of invasion is more restricted. In areas of the north Atlantic where the tidal amplitude may reach or exceed 3.0 meters, plants are restricted to the upper one-half or less of the tidal zone. On the southern Pacific coast (Fig. 1) marsh plants seldom extend below the elevation of mean tide even in

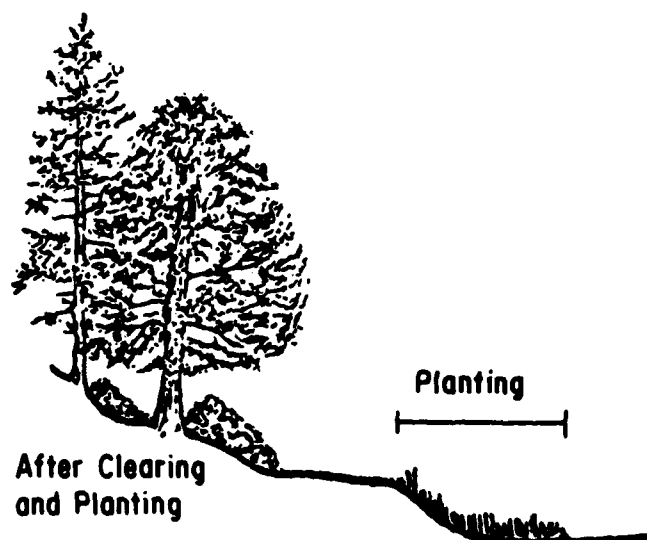
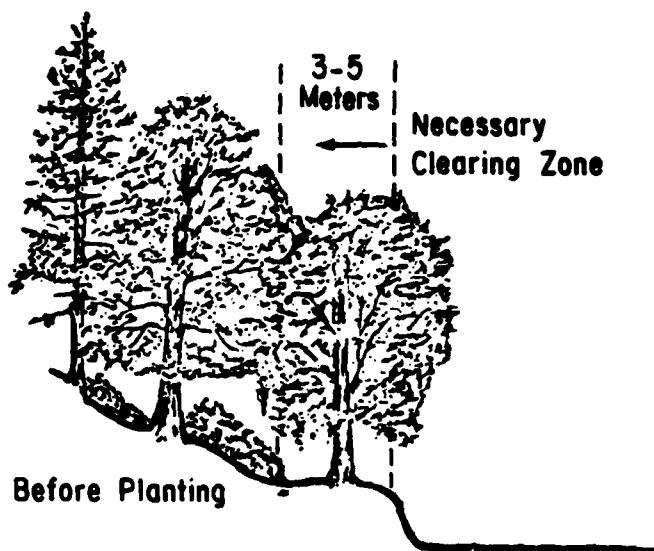


Figure 11. Clearing woody vegetation to provide direct sunlight exposure.

areas with a tidal amplitude of less than 2.0 meters. In the northern Pacific coast (Fig. 1) most of the intertidal zone lacks marsh vegetation because of the influence of large tidal ranges and the absence of suitable adapted species. Marshes are rarely found below the elevation of mean lower high water (MLHW) in this region.

Even when plants can be established throughout much of the intertidal zones, as is the case on many of the Atlantic coast marshes, the potential width (landward to seaward) of a particular planting depends on the tidal amplitude and shore slope. Broader marshes can be established coincident with greater tidal ranges and more gradual sloping shorelines.

d. Sediment Supply. Rapidly prograding salt marshes normally occur only in the presence of an abundant sediment supply. However, healthy salt and brackish marshes are found under a very wide range of sediment conditions. Removal of some sediment from a marsh shoreline is usually inevitable during storm periods. For such areas to remain stable this lost material must be recaptured from time to time, e.g., at regular intervals, between storm events, or seasonally as the result of wind-driven or tidal currents. Sediments may move in suspension or as bedload. There are no guidelines at present for evaluating the sediment supply of prospective planting sites.

e. Summary.

(1) Soil Type. Salt marsh plants are tolerant to a wide variety of soil types. However, soil type often dictates the choice of planting and fertilization procedures that will be necessary.

(a) Cohesive Sediments (Clays). Cohesive sediments provide a stable planting surface and are low in nutrients if highly weathered and are more difficult to plant than loose sandy substrates.

(b) Sandy Sediments. Sandy sediments may provide an unstable planting surface if subject to high wave activity, are low in nutrients, and are easy to plant if not compacted.

(2) Salinity. Suitable plants may be found which can be established in salinities up to about sea strength (35 parts per thousand).

(3) Oxygen-Aeration. Most marsh species are adapted to anaerobic conditions.

(4) Exposure to Direct Sunlight. The overstory of woody vegetation, if present, should be cleared above the planting area and to a distance of 3 to 5 meters landward.

(5) Shore Width Available for Planting. A practical minimum planting width for erosion control planting is about 6.0 meters.

(6) Sediment Supply. The sediment supply is beneficial to marsh stability but difficult to quantify.

2. Evaluation Wave Climate Severity.

It is a complex task to describe wave environments in which vegetative stabilization will be effective. The only method available for determining the growth of wind-generated waves in relatively shallow water is empirical (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977). There are many physical and biological variables which must be acknowledged when comparing wave climate to plant survival. The tidal elevation coincident with a particular set of waves, as well as shore geometry and sediment grain size, will greatly influence the stress placed on plantings. Also, the ability of a planted area to withstand wave stress will depend on its growth stage, density, vigor, and overall width.

Little definitive information is available concerning wave climates in which vegetation is likely to be an effective stabilizer. It is generally held that vegetation will successfully control erosion only in areas which are exposed to low and moderate wave stresses. However, this generalization does not allow a thorough engineering consideration of this alternative on a project-by-project basis.

In order to establish a criteria for assessing wave climate on an individual project basis, Knutson, et al. (1981) conducted a survey of 86 marsh planting sites in 12 coastal states. The shoreline characteristics of fetch, shore configuration, and sediment grain size were found to be the most useful indicators of wave climate severity and the likelihood of planting success. Though these parameters are proven indicators of planting potential, other characteristics such as local winds, boat traffic, offshore depth, and tidal currents should also be considered during site evaluation. The following sections describe the principal shore characteristics that influence the growth and decay of waves and the impact waves have on erosion control plantings.

a. Fetch. For the coastal engineer, fetch (the horizontal distance the wind blows over water to generate waves) is an important parameter in estimating wave height. The height of a wave formed by a constant wind blowing over water of a constant depth is directly related to fetch length (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977). This relationship is not linear. For example, a constant wind blowing 50 kilometers per hour (13.9 meters per second) over a constant water depth of 6 meters will generate a 15-centimeter wave over a fetch of about 150 meters, and a 30-centimeter wave over 750 meters, a 45-centimeter wave over 2125 meters, and a 60-centimeter wave over 4575 meters. As fetch length increases, it has incrementally less influence on wave height.

Knutson, et al. (1981) found that fetch length was inversely related to successful erosion control (Figs. 12 and 13). Eighty-nine percent of plantings exposed to a longest fetch of less than 2.0 kilometers were either successful or partially successful (no erosion landward but evidence of erosion on the seaward edge of planting). Conversely, 83 percent (five out of six) of the sites with a fetch of more than 18.0 kilometers were failures.

b. Shore Configuration. Shore configuration (the shape of the shoreline) can influence wave attack on the shoreline. Sites located in narrow coves may be effectively sheltered from waves approaching at oblique angles and will be

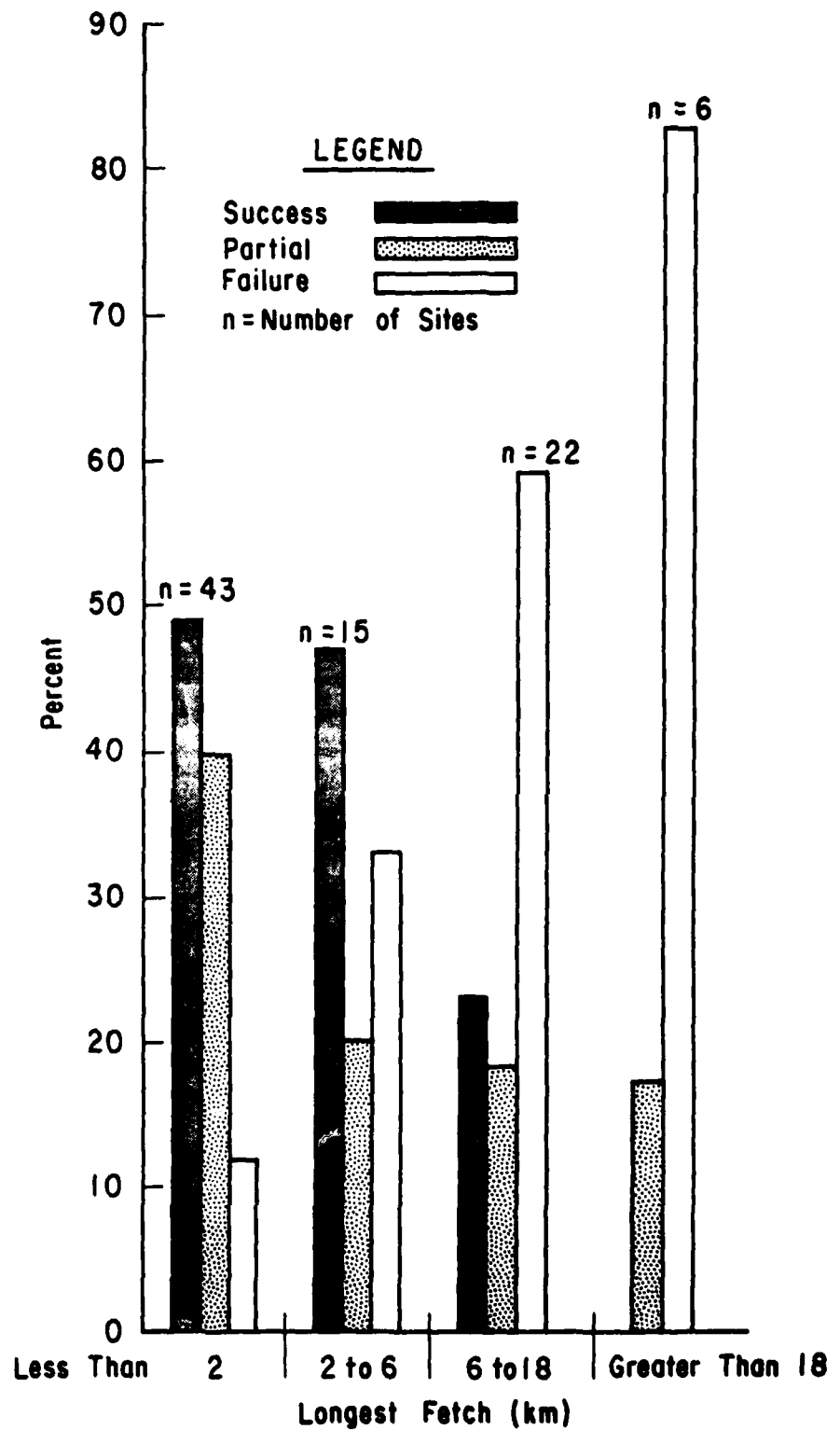


Figure 12. Planting performance versus longest fetch.

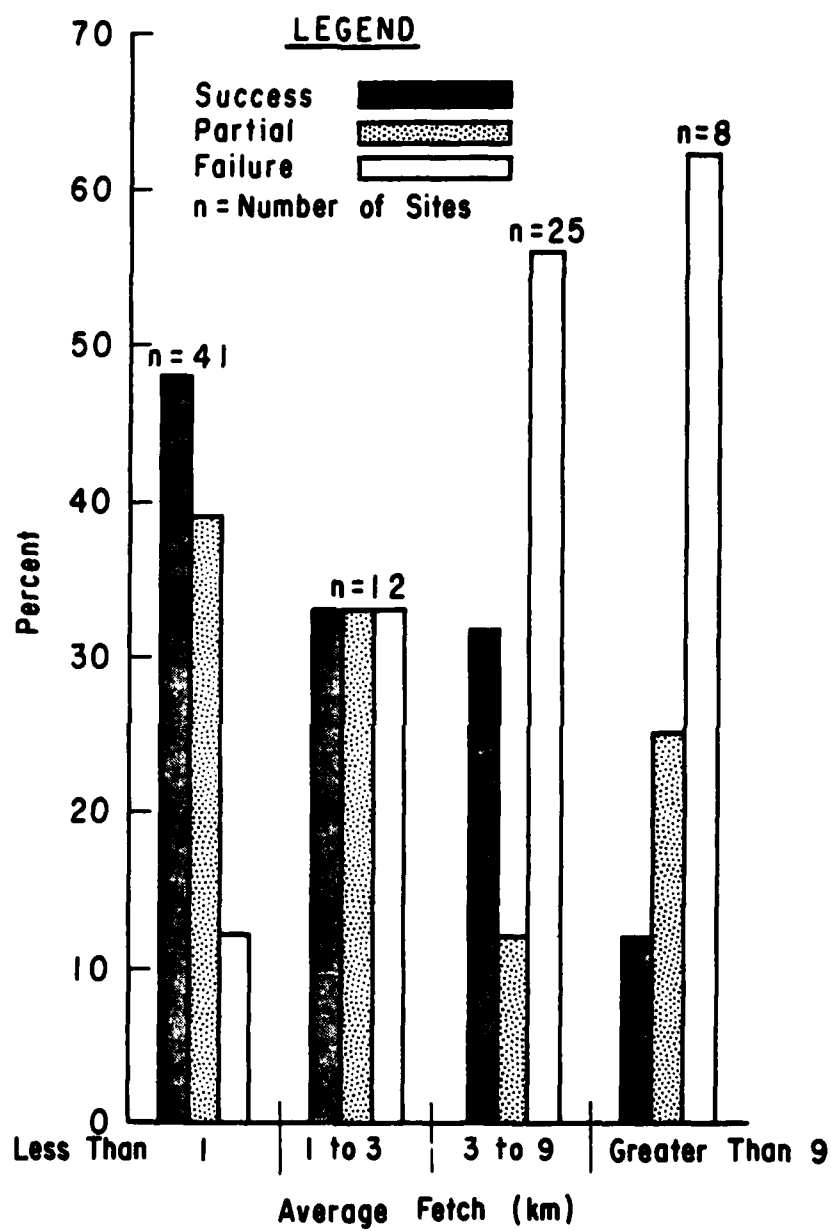


Figure 13. Planting performance versus average fetch.

subjected to large waves only when winds blow directly onshore. Conversely, sites located on headlands are exposed to waves from many directions. Figure 14 illustrates the relationship observed between shore configuration and successful erosion control (Knutson, et al., 1981). Eighty-five percent of plantings in coves were either successful or partially successful.

c. Sediment Grain Size. In general, low-energy beaches tend to have finer grained sediments and a more steeply sloping foreshore. High-energy beaches tend to have coarser sediments and more gradual sloping foreshores (Wiegel, 1965). Slope and grain size are, therefore, potential indicators of wave climate. Knutson, et al. (1981) found the grain size of the swash zone (the zone of wave uprush) sediments to be an indicator of site planting potential (Fig. 15). Eighty-four percent of the planted sites with mean grain-size values of less than 0.4 millimeter were successful or partially successful. Conversely, 82 percent of sites above 0.8 millimeter were failures. Measurements of shore slope have not been found to be reliable indicators of planting success.

d. Winds. Winds moving over water transfer energy to the water surface in the direction of the wind. Each geographical region has a characteristic wind climate. Local wind roses are useful in determining the direction from which predominant winds and the most severe storm winds occur. Although wind roses in close proximity to a project area are not always possible to obtain, knowledge of the direction of predominant winds and storm winds can be helpful. No general methods of interpreting these data to forecast planting success have yet been developed.

e. Ship-Generated Waves. Shore areas in close proximity to ship traffic will be subject to ship-generated waves. The height of waves produced by a given vessel depends primarily on the speed of the ship and, to a lesser extent, on the hull form, draft, and water depth below the keel (Sorensen, 1973). The wave climate produced by vessels at a particular shore site will depend on the magnitude of the ship-generated waves, traffic frequency, and the distance between the shore and the vessels (Table 1).

Of particular importance in Table 1 is the fact that relatively small vessels, such as the cabin cruiser, can produce waves comparable to those of larger craft, such as the fire boat, if the two are proceeding at similar speeds. Table 1 also illustrates that maximum wave height is significantly less at a 150-meter distance from the sailing line than it is at a 30-meter distance. Overall, wave height was reduced from 25 to 50 percent at the 150-meter distance. Though local boating patterns should be considered in determining site suitability, there are no guidelines for using this information to forecast planting success.

f. Offshore Depth. Offshore depths have a substantial effect on the height of waves that a particular storm will generate. Theoretically, a constant 13.9-meter-per-second wind blowing over water with a constant depth of 1.5 meters for a distance of 16 kilometers will generate waves less than 0.5 meter in height (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, in preparation, 1983). The same conditions for a constant depth of 12 meters will produce waves 0.8 meter high. Therefore, shore areas with shallow offshore depths will be more easily stabilized.

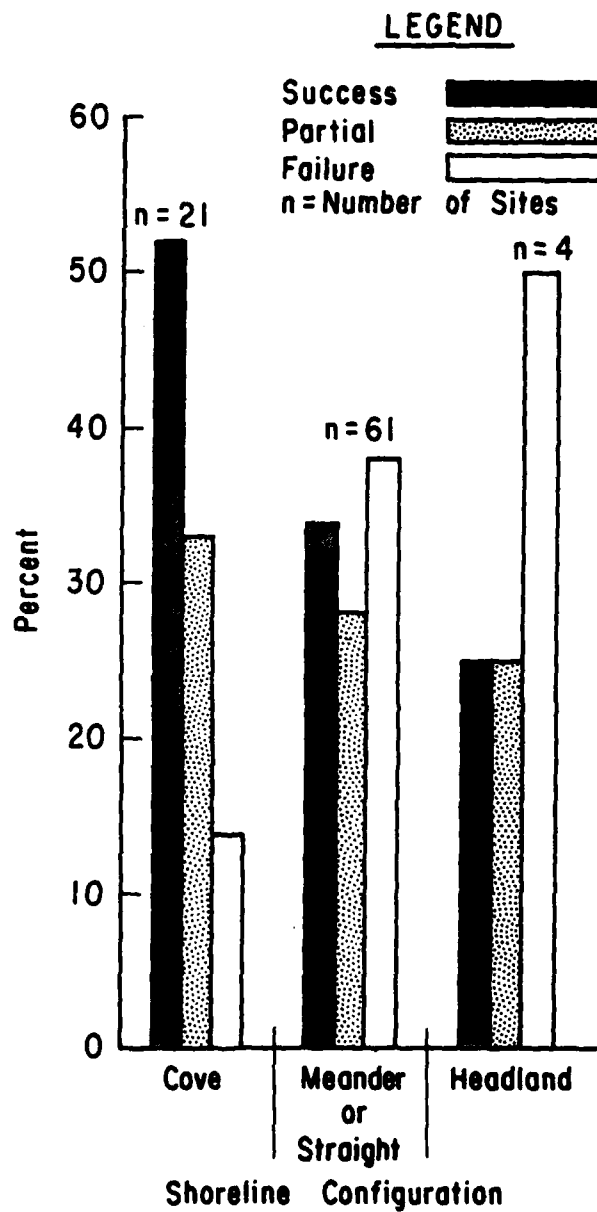


Figure 14. Planting performance versus shoreline configuration.

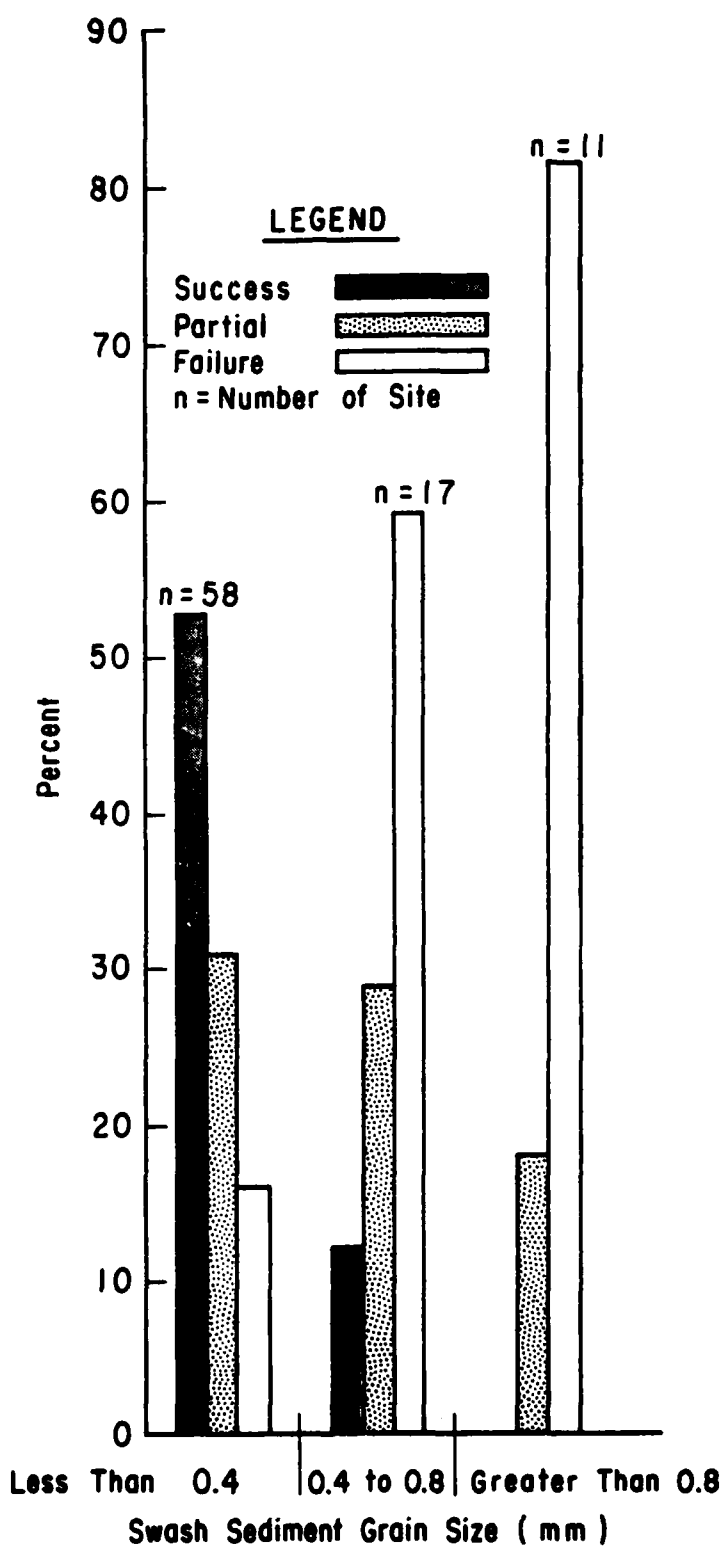


Figure 15. Planting performance versus sediment grain size.

Table 1. Waves heights produced by three vessels
(after Sorensen, 1967).¹

Vessel type	Displacement		Speed	Distance from sailing line	
				30 m	150 m
	(kn)	(ton)	(m/s)	Max. wave height (m)	Max. wave height (m)
Cabin cruiser	27	3	3.1	0.2	0.1
			5.1	0.4	0.2
Reconverted air-sea rescue vessel	310	35	3.1	0.1	-
			5.1	0.4	0.2
Fireboat (reconverted tug)	3050	343	3.1	0.1	0.1
			5.1	0.5	0.3

¹Water depth was approximately 12 meters.

g. Tidal Currents. Planting failures for otherwise favorable sites often result from the action of tidal currents. Marsh plantings as well as established marshes are particularly vulnerable to undermining by strong tidal currents. The location and potential migration of tidal channels in the vicinity of prospective plantings should be considered.

h. Discussion. Planting will be successful along some shorelines with unfavorable characteristics just as plantings along some shorelines with favorable characteristics will fail. Consequently, it is advisable to examine prospective sites carefully for unusual features that may affect planting feasibility. For example, some sites are subjected to elevated water levels (wind setup) during most periods of strong onshore winds. It has been possible to establish bands of marsh within the intertidal zone, which is below the most violent wave action, on some of these shores. Here erosion may continue for some time above and behind the planted marsh but the eroding sediments are trapped by the marsh, thereby widening and strengthening it. As this continues wave attenuation will increase and the eroding zone will eventually become either stabilized naturally or ready for planting. *The presence of patches of healthy marsh on or near the site is an indication that the site is plantable.*

Achieving successful erosion control with vegetation often requires both perseverance and patience. First, severe storms during establishment may cause temporary setbacks, even on highly promising sites, but these setbacks should not discourage the planter. More formidable and expensive coastal engineering structures are often damaged by the untimely occurrence of severe storms. In most cases storm damage in plantings can be repaired by replanting the damaged areas. Second, a planting will require 1 to 3 years to achieve stability. A rapid establishment on difficult sites should not be expected.

i. Summary. No single parameter or list of parameters can accurately predict the success or failure of a planting. It is, rather, a question of odds and probabilities. Under the best conditions the success of a planting

will be influenced by factors such as (1) the care taken by the planter, (2) the occurrence of severe storms, (3) the impact of foot and vehicular traffic, and (4) the wildlife predation.

As noted earlier, fetch, shore configuration, and sediment grain size appear to be useful indicators of wave climate severity and the potential of planting success. The relationship between these parameters (Figs. 12 to 15) and success in controlling erosion (successful or partially successful) have been condensed into a single form, the Vegetative Stabilization Site Evaluation Form (Fig. 16). This allows the user to estimate the potential success rate of plantings made under conditions similar to the site being evaluated. The user measures each shore characteristic (item 1) for the area in question, identifies the descriptive categories (item 2) which best describe the area, notes the success rate (item 3) associated with each descriptive category, calculates a cumulative score (item 4), and interprets the cumulative score by noting the corresponding success rate (item 5). The major advantage of this system is that it is easy to use.

The reader is cautioned that the evaluation form is used only for evaluating wave climate. Other shore conditions and characteristics discussed earlier in this section must also be considered in the total site evaluation process.






IV. SELECTING PLANT SPECIES, PLANT MATERIALS, AND PLANTING TECHNIQUES

1. Selecting Plant Species.

a. Principal Species. In the planting of salt marsh for the protection of eroding shorelines, the intertidal zone is critical. This is the region in which erosion normally begins; continuing erosion of the lower slopes in this region will undermine and weaken well-stabilized upper slopes. Consequently, the primary emphasis will be on the planting and management of the few specially adapted species found useful for this purpose. Often the establishment and maintenance of a healthy band of intertidal salt or brackish marsh along a shore will eventually result in the natural growth of vegetation on the slope behind it.

Four species of pioneer plants have demonstrated potential in stabilizing the part of the intertidal zone which is in direct contact with waves. Smooth cordgrass (*Spartina alterniflora*) is an effective erosion control plant along the gulf and Atlantic coasts, Pacific cordgrass (*Spartina foliosa*) is effective on the southern Pacific coast from Humboldt Bay, south to Mexico, and Lyngbye's sedge (*Carex lyngbyei*) and tufted hairgrass (*Deschampsia caespitosa*) are effective for stabilization in the northern Pacific coast from Humboldt Bay to Puget Sound. Detailed planting specifications for these principal species are given in Section VI.

b. Other Useful Species. There are cases in which the planting of an entire slope is advisable to control erosion caused by storm surges, surface runoff, and wind, or is desirable for esthetic or other reasons. Planting can restore vegetation on the slope immediately above the high tide line when damage has occurred during site preparation. Planting will be required in some instances as protection against runoff from adjacent uplands. Several

1. SHORE CHARACTERISTICS		2. DESCRIPTIVE CATEGORIES (SCORE WEIGHTED BY PERCENT SUCCESSFUL)				3. WEIGHTED SCORE
a. FETCH-AVERAGE <small>AVERAGE DISTANCE IN KILOMETERS (MILES) OF OPEN WATER MEASURED PERPENDICULAR TO THE SHORE AND 45° EITHER SIDE OF PERPENDICULAR</small> 		LESS THAN	1.1 (0.7) to 3.0 (1.9)	3.1 (1.9) to 9.0 (5.6)	GREATER THAN	
		1.0 (0.6)		9.0 (5.6)		
		(87)	(66)	(44)	(37)	
b. FETCH-LONGEST <small>LONGEST DISTANCE IN KILOMETERS (MILES) OF OPEN WATER MEASURED PERPENDICULAR TO THE SHORE OR 45° EITHER SIDE OF PERPENDICULAR</small> 		LESS THAN	2.1 (1.3) to 6.0 (3.7)	6.1 (3.8) to 18.0 (11.2)	GREATER THAN	
		2.0 (1.2)		18.0 (11.2)		
		(89)	(67)	(41)	(17)	
c. SHORELINE GEOMETRY <small>GENERAL SHAPE OF THE SHORELINE AT THE POINT OF INTEREST PLUS 200 METERS (660 FT) ON EITHER SIDE</small>						
		(85)	(62)	(50)		
d. SEDIMENT¹ <small>GRAIN SIZE OF SEDIMENTS IN SWASH ZONE (mm)</small>		less than 0.4	0.4 - 0.8	greater than 0.8		
		(84)	(41)	(18)		
4. CUMULATIVE SCORE						
5. SCORE INTERPRETATION						
a. CUMULATIVE SCORE		122 - 200	201 - 300	300 - 345		
b. POTENTIAL SUCCESS RATE		0 to 30%	30 to 80%	80 to 100%		

¹Grain-size scale for the Unified Soils Classification (Casagrande, 1948; U.S. Army Engineer Waterways Experiment Station, 1953):

Clay, silt, and fine sand - 0.0024 to 0.42 millimeter

Medium sand - 0.42 to 2.0 millimeters

Coarse sand - 2.0 to 4.76 millimeters.

Figure 16. Vegetative Stabilization Site Evaluation Form.

potentially useful species that may be used to supplement erosion control plantings are listed below:

- (1) Black needle rush (*Juncus roemerianus*).
- (2) Common reed (*Phragmites communis*).
- (3) Cordgrasses: Big cordgrass (*Spartina cynosuroides*); gulf cordgrass (*Spartina spartinae*); saltmeadow cordgrass (*Spartina patens*).
- (4) Mangroves: Red (*Rhizophora mangle*); black (*Avicennia germinans*); white (*Laguncularia racemosa*).
- (5) Saltgrass (*Distichlis spicata*).
- (6) Seaside arrowgrass (*Triglochin maritima*).
- (7) Siltgrass (*Paspalum vaginatum*).

The need to plant these species should be evaluated for each individual site. Planting specifications and guidelines for the use of these other useful species are given in Section VI.

2. Selecting Plant Materials.

Choosing the type of planting materials and determining a source of suitable planting stock should be done early in the planning process. The cost of planting stock usually represents a substantial part of the total expense and this cost can vary over a wide range. Locating a suitable source of plants may be the most difficult problem to be solved. The practice of salt marsh planting is still in the embryonic stage in this country. Both the development and the demonstration of planting techniques are very recent. Although a substantial number of successful field-scale plantings have been made, this has not yet become a standard practice. Therefore, the demand for planting stock is still small, erratic, and unpredictable. Consequently, such materials are not generally available commercially; there are a few nurseries that produce plant materials on order.

Marsh plants are propagated either by seeds or by some type of vegetative transplant. Since direct seeding is effective only under fairly sheltered conditions the planting of eroding shorelines must be confined to the following vegetative transplants: (a) sprigs, which are bare root plants dug from field nurseries or from the wild (Fig. 17); (b) pot-grown seedlings; or (c) plugs, which are root-soil masses containing several intact plants dug from the wild. There is no one best type of planting stock. The quality of the material is often the key to success. High-quality material in any form can be very successful. High quality in this context means young, vigorous, actively growing vegetation that is large enough to carry appreciable stored food reserves. Early initiation of new growth is essential if transplants are to establish under the rigorous conditions existing on most eroding shorelines. This new growth cannot be expected of old or stunted plants, regardless of transplant form. Choice of plant material type may in a few cases be



Figure 17. Typical smooth cordgrass transplant or "sprig" from the wild or from an intertidal nursery.

affected by species and this aspect will be discussed later in connection with planting specifications for individual plants.

The three types of planting stock (sprigs, pot-grown seedlings, and plugs) vary in availability, cost, and ease of planting:

(a) Sprigs are the least expensive of the three types and easier to handle, transport, and plant. They must be obtained either from field nurseries (planted a year or more in advance) or from young developing natural stands, or from along the edges of stable or expanding marshes. Sprigs can only be dug satisfactorily from sandy substrates.

(b) Pot-grown seedlings are more expensive to grow and plant, more awkward to handle and transport, but relatively easy to produce. Seedlings of most species can be grown to transplanting size in 3 to 5 months and this can be done almost anywhere with very simple, inexpensive facilities and equipment. However, their cost is usually at least two to five times that of sprigs. Seedlings become increasingly expensive to carry over when transplanting is delayed. Repotting in larger containers soon becomes essential. The coordination of plant production and site preparation is a frequent stumbling block in the use of seedlings.

(c) Plugs are the most expensive planting type; the cost is usually about twice the cost of pot-grown seedlings. Plugs are laborious to dig, heavy, difficult to transport, and harder to plant. Satisfactory plugs can only be dug from marshes growing on cohesive substrates. Plugs from old crowded stands are likely to be too slow in initiating new growth. However, plugs are often more resistant to uprooting during the establishment period and are sometimes the only planting stock available on short notice.

3. Selecting Planting Techniques.

The essentials in successfully transplanting salt marsh plants include opening a hole or furrow deep enough to accommodate the plant to the required depth, keeping the hole open until the plant can be properly inserted to the full depth, closing the opening, and firming the soil around the plant. This operation should be done during low water, as it is virtually impossible to do a satisfactory job of transplanting while the surface is flooded. Openings can close too rapidly and plants tend to float out. There are a number of tools and procedures that work well in substrate that is not flooded.

Hand planting can be very satisfactory if adequate attention is given to details, particularly planting depth and soil firming after planting (Fig. 18); it is usually the most practical method for small-scale plantings. Opening of planting holes is readily done with dibbles, spades, and shovels in loose, sandy soils. Portable power-driven augers work well in the more difficult cohesive or compact soils. Normally planting crews work in pairs, one worker opening holes and the other inserting the plant and closing the hole. A third worker is used if fertilizer is added in the planting hole; the third worker drops in a measured amount of material just after the hole is opened and before the plant is inserted.



Figure 18. Planting by hand.

Machine planting, where feasible, can do a much more uniform job and is far more economical than hand planting in large-scale planting (Fig 19). Tractor-drawn planters designed to transplant crop plants such as cabbage, tomatoes, and tobacco are available in most regions. Although some may require an alteration of the row opener for certain soils, they can often be used without alteration. The principal barriers to machine planting are usually inadequate traction on compact substrates, insufficient bearing capacity on soft sites, or the presence of tree roots or stones that interfere with the functioning of the row opener.

Planting depth is not critical on sheltered sites. Most species will develop satisfactorily when planted 2 to 5 centimeters deeper than their depth when originally dug or removed from pots. However, in planting exposed shores, it is often highly desirable to anticipate erosion or accretion trends that are likely to prevail during the first month or two after planting. Where erosion is expected, plants should be set even deeper than the 2- to 5-centimeter depth. Where deposition is likely they should be set very close to their original depth when dug or removed from pots. Woody vegetation such as mangroves should not be set much lower than their growing depth.

4. Summary.

a. Principal Erosion Control Species:

- (1) Atlantic and gulf coasts - smooth cordgrass (*Spartina alterniflora*).
- (2) Southern Pacific coast - Pacific cordgrass (*Spartina foliosa*).



Figure 19. Mechanical planting with disk-type tobacco planter.

(3) Northern Pacific coast - Lyngbye's sedge (*Carex lyngbyei*) and tufted hairgrass (*Deschampsia caespitosa*).

b. Plant Materials:

(1) Sprigs - least expensive to obtain and easier to handle, transport, and plant.

(2) Pot-grown seedlings - more expensive to grow and plant, more awkward to handle and transport, but relatively easy to produce.

(3) Plugs - most expensive to obtain, difficult to transport and plant; only used when other sources are not available.

c. Planting Methods:

(1) Hand planting (dibbles, spades, and shovels) - suitable for all plant materials.

(2) Power-driven auger - useful for difficult soils and for pot-grown seedlings and plugs.

(3) Machine planting (cabbage, tomato, and tobacco planters) - very efficient for large-scale plantings of sprigs; most can be equipped to handle seedlings.

V. FERTILIZATION REQUIREMENTS

The possible use of fertilizers warrants careful consideration in the planning of any marsh establishment project. Its use may be essential to

success and may affect the planting procedure. The goal of marsh planting on eroding shores is to speed up the establishment process under conditions which have discouraged or prohibited natural invasion. An ample supply of nutrients is one key element in assuring the accelerated rate of growth that is usually required. Fertilization is primarily an establishment tool and is usually necessary for nutrient-deficient soils along high-energy shores only.

Nutrient deficiencies are much more prevalent in the subsoil materials exposed along eroding shorelines than in dredged materials or alluvial deposits. For this reason, the use of fertilizers in erosion control plantings should be considered to be prudent insurance unless it is clearly determined to be unneeded. Observed response to the application of nutrients on marsh plantings under brackish and saltwater conditions has been limited to nitrogen and phosphorus. Benefits from the addition of potassium or micro-nutrients have not been identified and appear unlikely. Soil tests used to estimate available phosphorus in agricultural soils appear to be fairly reliable in identifying the extremes in intertidal soils, i.e., the acutely deficient soils and the soils well supplied with phosphorus. There are, however, no practical testing procedures that can be relied upon to predict available soil nitrogen. If information is lacking on similar soils nearby, the only safe approach is to add nitrogen or, as a minimum, apply it to a part of the planting and carefully observe the results.

1. Types of Fertilizer.

The lack of reported information on the response of salt marsh plants to fertilization in some cases is due to the use of unsuitable forms of nitrogen. Nitrate undergoes rapid denitrification under anaerobic conditions and may be quickly lost (Patrick and Makaputra, 1968). Also, ammonia is utilized more efficiently than nitrate by smooth cordgrass, which is just the reverse of most upland plants (Gosselinck, 1970; Woodhouse, Seneca, and Broome, 1976; Mendelsohn, 1979). This is probably true of other marsh species because ammonia is the normal form of nitrogen existing under anaerobic conditions. Ammonium sulfate is commercially available and is usually an economical source of nitrogen for marsh use. Diammonium phosphate should be an equally good source. The urea and ureaformaldehyde forms of nitrogen were found to be ineffective in marsh fertilization in recent tests (Broome, Seneca, and Woodhouse, in preparation, 1983).

The form of phosphorus used in marsh fertilization is not critical. The solubility of most phosphorus compounds is enhanced by an anaerobic environment. Acute phosphorus deficiencies can usually be anticipated through soil tests. Also, high phosphorus fixation is usually indicated by the presence of a yellowish or reddish substrate rather than the dark colors of reduced soils. Any of the standard soluble phosphatic fertilizers such as concentrated superphosphate and diammonium phosphate are satisfactory and economical.

Some slow-release fertilizers can be useful in marsh planting. Broome, Seneca, and Woodhouse (in preparation, 1983) found osmocote and magnesium-ammonium-phosphate (mag-amp) to be very effective on intertidal marsh, when applied in the planting hole or furrow. Osmocote is a soluble fertilizer, 60 percent ammonia and 40 percent nitrate, encapsulated with multiple polymeric, semipermeable coatings. The slow-release characteristics of mag-amp are due to its low solubility, which can be controlled through granule size. It is

not advisable to apply these fertilizer materials on a soil surface that may be subject to wave and tidal action. Considered convenient because they require fewer applications, these materials may permit lower rates, particularly of nitrogen, and may have a larger carryover effect into the succeeding growing season. Although slow-release fertilizers are much more expensive than conventional fertilizers, in some cases they produce better results than less costly soluble sources (Broome, Seneca, and Woodhouse, in preparation, 1983).

2. Placement of Fertilizer.

Broome, Seneca, and Woodhouse (in preparation, 1983) found surface application (topdressing) to be ineffective, even of soluble materials on a compact sandy, clay loam soil in the planting year. Evidently, the nutrients did not penetrate rapidly enough and a root mass was not available soon enough to absorb them. Surface application on cohesive sediments is also likely to be ineffective during the first year. The most effective placement of fertilizer in the year of establishment on all soils is probably in the planting hole or furrow. This allows the nutrients to be close to the developing root systems and minimizes losses from surface runoff and erosion. However, the intimate mingling of soluble fertilizers with the plant roots may pose a danger of salt damage in compact or cohesive sediments, even though these plants possess a high tolerance to salt. To avoid this problem soluble materials should be broadcast and disked in prior to planting, spread in the planting furrow, placed in a second hole beside the planting hole, or placed in the bottom of the planting hole and covered with soil before the plant is inserted. Salt damage can be a problem, even in the absence of fertilizer, on marsh plants growing on sites subject to extended periods of low water caused by wind setdown or reduced streamflow (Woodhouse, 1979). Placement in the planting hole should be limited to slow-release materials in these situations and in planting high marsh species.

Surface application of soluble fertilizer materials is effective on loose sandy soils in the planting year (Woodhouse, Seneca, and Broome, 1976). However, application of fertilizers to the soil surface should be delayed for a month or so after transplanting to allow transplants to develop new roots. Such topdressing is done on the exposed surface during low tide. Surface application of soluble fertilizers is very effective on established marsh. Broome, Seneca, and Woodhouse (in preparation, 1983) found that even where the surface application of fertilizer at planting was ineffective, a topdressing the following spring doubled aboveground biomass by the end of the growing season. The extensive root systems, together with the dense aboveground growth, combined to retain much of the fertilizer. Fertilizer that was not initially absorbed would have soon been covered by accumulating sediments.

3. Fertilizer Rates.

The rate of application of fertilizers on marsh plantings for shoreline erosion control should be high enough to insure that nutrient supply will not be a limiting factor in the rapid establishment of transplants. The cost of such fertilizer will be low in relation to the total cost of the planting and even lower in relation to the cost of failure. For this reason, if fertilizers are to be used, they should be applied at ample rates, but not excessively or in wasteful amounts of nutrients.

Response of marsh planting to rates of nitrogen is much more pronounced than is phosphorus response. Growth of nitrogen-deficient stands of smooth cordgrass in sandy substrates has been increased by nitrogen applications up to 6 kilonewtons per hectare (600 pounds per acre) per year. Practical levels of nitrogen for establishment are much less, probably in the range of 1 to 3 kilonewtons per hectare (100 to 300 pounds per acre). While there are no reliable chemical tests for available nitrogen, the color of the grass itself after establishment can be a useful indicator of nitrogen status. Dark green leaves are usually well supplied with nitrogen. Lighter shades of green accompanied by the yellowing of lower leaves during the period of active growth usually indicate inadequate nitrogen; however, this should not be confused with the normal yellowing or browning that develops as most marsh grasses and sedges mature.

Phosphorus response is less common than nitrogen response and, where needed, lower rates and less frequent application of this nutrient are usually required. Broome, Seneca, and Woodhouse (in preparation, 1983) obtained maximum growth of smooth cordgrass with the application of about 1 kilonewton per hectare of phosphate on a soil extremely deficient in this element. It is doubtful that a greater amount than this in any 1 year would ever be warranted.

If soluble materials (ammonium sulfate and concentrated superphosphate or diammonium phosphate) are used, they should be applied at a rate of 1 kilonewton per hectare of nitrogen and 1 kilonewton of phosphate at time of planting (3 to 4 weeks after planting if fertilizer is applied as a topdressing). In conventional mixed fertilizers, such as 10-10-10, the number designations represent the percentages (by weight) of nitrogen (N), phosphate (P_2O_5), and potash (K_2O), respectively, that are found in the mixture. Therefore, the amount of 10-10-10 fertilizer per hectare needed to provide 1 kilonewton each of nitrogen and phosphate would be 10 kilonewtons (1,000 pounds per acre or about 2.3 pounds per 1,000 square feet). A topdressing of an additional 1 kilonewton per hectare of soluble nitrogen, 6 to 8 weeks after planting, will be helpful on deficient sites; a third application of 1 kilonewton 6 weeks later will be advisable on acutely deficient sites. If conventional mixed fertilizers are not used, phosphorous may be applied with the first application of nitrogen or it may be combined with the split applications of nitrogen.

Slow-release materials, if used in lieu of soluble fertilizer, should be applied at a rate of 1 kilonewton per hectare of nitrogen at the time of planting. Slow-release materials should always be placed in the planting hole or furrow. For conventional slow-release mixtures (14-14-14 or 16-8-12), about 0.15 newton (0.5 ounce) of fertilizer should be placed in each planting hole or along each 0.5 meter of the planting furrow. When slow-release materials are used, no additional applications are necessary during the first growing season.

4. Maintenance Fertilizer.

The use of fertilizer to aid marsh establishment is usually confined to the year of planting. As soon as the new plants grow enough to begin significant sediment accumulation, the need for fertilizer usually decreases sharply or disappears. Thereafter, the native supply from substrate, accumulating

sediment, and surrounding waters is usually adequate to maintain moderate growth, at least, and this is often sufficient for stabilization purposes. However, the application of fertilizer can be very helpful to marsh plants in tolerating or overcoming stress where the nutrient supply is below optimum. Garbish, Woller, and McCallum (1975) states that maintenance fertilization is, at times, essential to enable established marsh stands to persist under high-energy conditions. Woodhouse, Seneca, and Broome (1976) found fertilizer to be very effective in overcoming the stunting effects of periodic salt buildup on smooth cordgrass. Broome, Seneca, and Woodhouse (in preparation, 1983) showed that the second year fertilization was essential to the establishment of a fully protective cover on a highly deficient, rapidly eroding, high-energy site.

Fertilization through the second year and perhaps in some succeeding years should always be considered where slow establishment and stress conditions threaten the maintenance of protective marshes. The amounts needed in such cases are likely to be less, no more than half, that required for marsh establishment. Such applications should consist of soluble materials and be broadcast in early spring. Fertilizers should always be applied when the soil surface is exposed by low tide.

5. Summary.

a. Types of Fertilizers:

(1) Ammonium sulfate, diammonium phosphate, osmocote, and mag-amp are good sources of nitrogen.

(2) Concentrated superphosphate, diammonium phosphate, osmocote, and mag-amp are satisfactory sources of phosphorus.

b. Placement: Place in planting hole or furrow during planting or top-dress at low tide, 1 month after planting when new roots have developed.

c. Rate: 1 to 3 kilonewtons of nitrogen (N) and 1 kilonewton of phosphate (P_2O_5) per hectare.

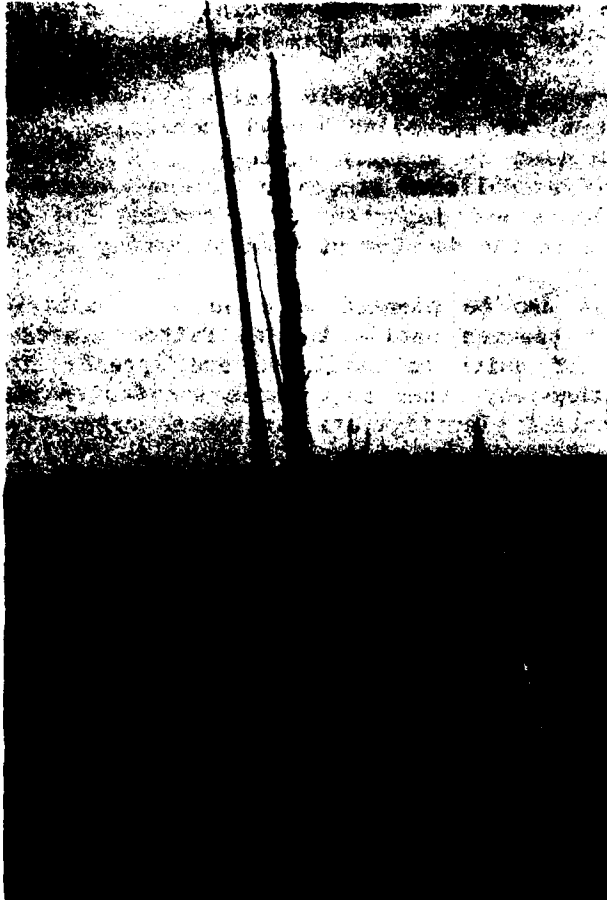
d. Maintenance: Not usually necessary but may improve a planting's resistance to wave stress.

VI. PLANTING SPECIFICATIONS FOR PRINCIPAL SPECIES

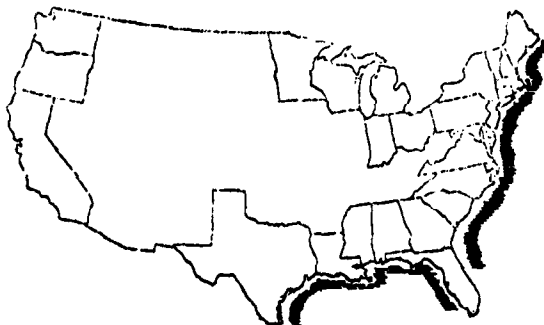
This section summarizes specifications for planting each of the principal species (smooth cordgrass, Pacific cordgrass, Lyngbye's sedge, and tufted hairgrass) used for shore stabilization and describes suitable planting techniques for each species. A brief summary of specifications is included following each section.

1. Smooth Cordgrass (*Spartina alterniflora*), Atlantic and Gulf Coasts.

Smooth cordgrass is the dominant flowering plant in the regularly flooded intertidal zone along the Atlantic coast from Newfoundland to about central Florida and along much of the gulf coast (Fig. 20). These marshes are essentially pure stands of smooth cordgrass. There are distinct geographic



a. Seed head (inflorescence)



b. Distribution (shaded area)

Figure 20. Smooth cordgrass.

populations of smooth cordgrass (Seneca, 1974) and seeds or plants for use on a given site should come from the same general area; e.g., it is not advisable to plant North Carolina material on Long Island.

Vegetative reproduction by extensive below-ground, hollow stems (rhizomes) is the primary method of spreading smooth cordgrass in established stands. Although seed production is usually limited in old dense stands, it may be substantial in newly established stands and along margins such as the borders of tidal creeks. Seeds are important in spreading the plant into new areas and often contribute to the density of open or patchy stands.

Smooth cordgrass can be planted with better chance of success than any other coastal marsh species native to the United States. It is relatively easy to propagate and quick to establish and spread. This grass tolerates inundation better than any other salt marsh species on the Atlantic and gulf coasts. Erosion control plantings are limited to vegetative material, such as sprigs, pot-grown seedlings, or plugs.

a. Planting Techniques.

(1) Sprigs. A sprig is a part of a plant consisting of at least one node (joint of a stem from which leaves arise) with attached stems and roots. Sprigs can be obtained from existing marshes or from nurseries established for this purpose. They are the least expensive plant type, the easiest to plant, and probably work better for smooth cordgrass than for any other marsh species. Sprigs must be large, robust plants to be effective.

Field-collected wild plants are satisfactory and often adequate for small-scale plantings. These should come from uncrowded stands, usually of recent origin, on sandy substrates. Plants are obtained by loosening individual clumps with a shovel, small back-hoe, or a plow and lifting and separating into individual transplants. Choice transplants consist of actively growing single stems (culms) large enough to carry substantial food reserves, with small shoots and short pieces of rhizomes left attached or discarded. Unattached rhizomes are of no value as propagules in the intertidal zone (Woodhouse, Seneca, and Broome, 1976). Digging and processing of planting stock from old, dense marshes is difficult and usually yields small, poor-quality plants. Where planting stock must be obtained from such stands, it is preferable to resort to plugs or cores because the small, single stems are not satisfactory as transplants (Woodhouse, Seneca, and Broome, 1974). A heavy harvest of single culm plants initially appears to be devastating to the stand. However, the effect is very short-lived, particularly in open, vigorous stands on sandy substrates; remaining rhizomes and shoots soon repopulate the area, usually in the same growing season. It is difficult to harvest such sites intensively enough to prevent overcrowding and reducing the suitability of the planting stock in succeeding years. Due to the rapid recovery of vigorous new stands, the harvesting of planting stock from year-old plantings for marsh building is often feasible. Such stands yield transplants of excellent quality at low cost with only a slight delay in the process of marsh development.

Field nurseries are relatively easy and economical to establish if suitable sites are available. An ideal site is a bare, smooth intertidal slope of sandy material along a relatively protected shore. The initial stand

may be established by seeding or transplanting single stems (Woodhouse, 1979). Sprigs may be hand-planted by inserting them 10 to 15 centimeters deep in holes opened by dibbles, spades, and shovels (Fig. 18) or planted in furrows by machine (Fig. 19), taking care to firm the soil around them immediately to prevent "float out." Planting is generally feasible only during low water when the substrate surface is exposed.

(2) Pot-Grown Nursery Seedlings. Nursery seedlings are plants grown from seed in peat moss or plastic pots under controlled conditions (Fig. 21). Three- to four-month-old seedlings are an alternative to sprigs. Five- to seven-month-old seedlings may be preferable to sprigs, particularly if transplanted late in the growing season. Pot-grown seedlings are relatively easy to produce but considerably more expensive than sprigs.

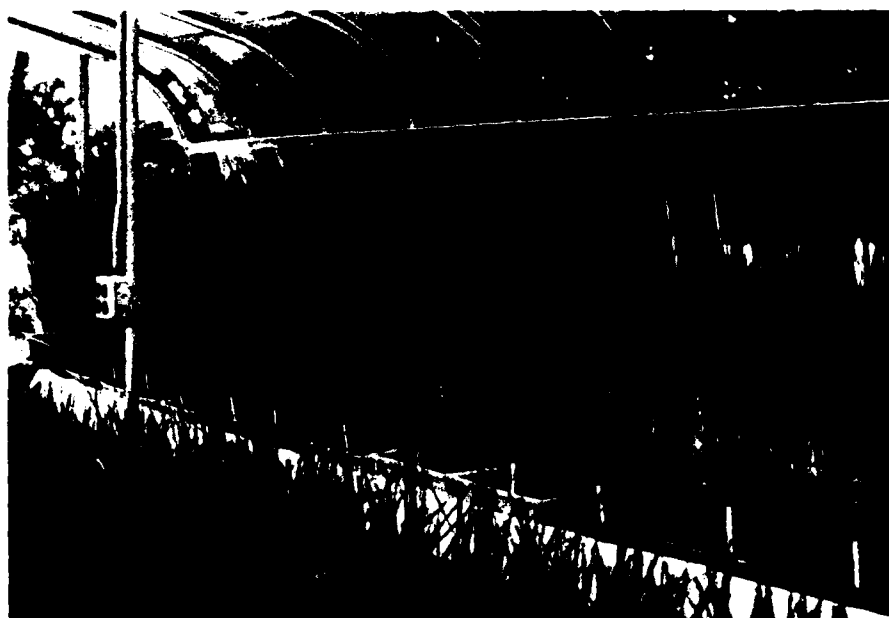


Figure 21. Pot-grown nursery seedlings (Environmental Concern Inc., St. Michael's, Maryland).

To prepare seedlings, seeds must be harvested (the cutting and collecting of seed heads) from existing stands of smooth cordgrass by wading or from boats (Fig. 22). This must be done shortly after maturity when seeds can be readily dislodged from the heads by rubbing as they shatter readily soon after. Heads should be stored moist, but not submerged, at 2° to 3° Celsius for 2 or 3 weeks to allow "afterripening." They may then be threshed to reduce storage space and facilitate handling, and stored in water of 20- to 25-parts-per-thousand salinity (Woodhouse, Seneca, and Broome, 1974) at 2° to 3° Celsius until planting time. Submerged storage is required because drying seeds rapidly lose viability (Mooring, Cooper, and Seneca, 1971), and saline water is preferable to retard germination during storage (Woodhouse, Seneca, and Broome, 1974). Low temperatures during storage are essential to retard germination as sprouting of ripe seeds is rapid under higher temperatures following afterripening. Even under the best storage conditions, large numbers

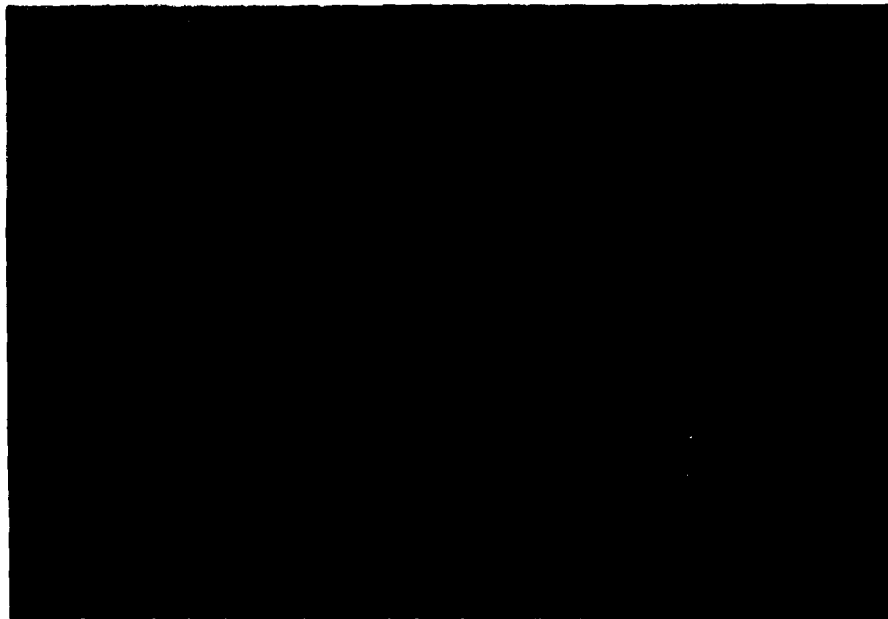


Figure 22. Harvesting seed.

of seed will sprout by the following March or April. These sprouted seeds are still usable for planting but are much more susceptible to damage from handling than unsprouted seeds. Freezing, either wet or dry, is not a satisfactory method of storage (Woodhouse, Seneca, and Broome, 1974). Viability of stored seed is not retained longer than 1 year. Consequently, seed to be planted the following year must be harvested in September of the previous year in northern latitudes and in November in southern latitudes.

Seed production is confined largely to new, open stands and along margins, e.g., along tidal creeks. The most vigorous stands usually produce the best seeds but variability is high. Planted areas usually yield heavy seed crops for several years following establishment. Seed heads are frequently damaged by parasitic infestation (ergot, *Claviceps purpurea*) and by flower beetles (family Mordellidae) (N. Newton, North Carolina State University, Raleigh, personal communication, 1976).

Flowering time and seed maturity progress from north to south, at least within geographic populations such as along the Virginia-Carolinas coast. For example, there is a spread of about 2 weeks, north to south, in seed maturity along the North Carolina coast with considerable variability within individual stands. Seeds are ready for harvest as early as September in the north Atlantic marshes and as late as November in the south Atlantic marshes but maturity varies from year to year.

Seeds may be broadcast over the surface of sandfilled, 5- to 10-centimeter-wide plastic or peat-moss pots and covered lightly, or they may be germinated in flats and transferred to the pots. Seeds should be removed from storage and soaked in 25 percent Clorox for 15 minutes, rinsed, and planted in

the 5-centimeter pots about 3 months before transplanting or 4 to 5 months before transplanting if 10-centimeter pots are used. Plastic containers are usually preferable to avoid intertwining of roots between pots. It is advisable to apply enough seed to provide 6 to 10 viable seeds per pot, but seedlings should be thinned to 2 to 4 per pot to avoid overcrowding. Excess seedlings may be transplanted to other pots. The pots should be irrigated with tapwater and fertilized after the seedlings emerge with 10-10-10 fertilizer, or a slow-release material may be mixed in the pot. If the seedlings are to be transplanted in site salinities above 15 parts per thousand, the solution should be adjusted with sodium chloride to maintain a salinity comparable to the site (Garbisch, 1977a; E Garbisch, Environmental Concern, Inc., personal communication, 1977).

Plastic pots should be discarded before planting and peat pots should be scored to encourage extension of the roots beyond the confines of the pot. Seedlings should be planted in holes opened with a shovel, spade, dibble, or auger. They can be planted by machine using a suitably equipped planter. Pots should be set slightly below the substrate surface and soil firmed tightly around them.

(3) Plugs. A plug is a root-soil mass, 10 to 15 centimeters in diameter and 15 to 20 centimeters deep, which contains roots and a number of stems. Plugs can be used as an alternative to the 5- to 7-month seedlings for late plantings, or as an alternative to sprigs where plants must be obtained from old, dense materials.

Plugs are harvested from existing marshes which have heavy-textured sediments. An intact root-soil mass cannot be maintained if plugs are excavated from noncohesive, sandy sediments. Culm size and vigor is important for plugs just as it is for sprigs and for the same reasons. One to three large culms per plug are always preferable to a larger number of smaller culms in the same size plug. Similar to potted seedlings, plugs should be planted slightly below the substrate surface and soil firmed tightly around them.

b. Soils and Salinity. Cordgrass is well adapted to sea-strength salinity (35 parts per thousand and also to the anaerobic substrates characteristic of most salt marshes. Its oxygen transport system consists of hollow, air-filled tissue, extending from openings in the leaves to the roots and rhizomes (Teal and Kanwisher, 1966; Anderson, 1974). Thus, oxygen reaches the below-ground tissues in anaerobic substrates. Cordgrass will grow in a wide range of substrates from coarse sands to silty clays to peats. Although dominant in regularly flooded, saline habitats, it is not restricted to these areas; it usually attains maximum growth under lower salinities (10 to 20 parts per thousand). The grass will grow and reproduce normally under freshwater conditions but is subject to increasing competition from other species as salinity declines (Woodhouse, Seneca, and Broome, 1974).

c. Planting Zone. Smooth cordgrass usually grows from MHW to near mean low water (MLW) in locations with narrow tidal ranges, and from MHW to MSL in locations with broader tidal ranges (Woodhouse, Seneca, and Broome, 1974). Table 2 is a summary of four observations of smooth cordgrass survival in lower intertidal areas. In each of the above areas water level fluctuations were principally a product of astronomical tides. In areas with pronounced

Table 2. Smooth cordgrass survival in lower intertidal areas.

Location (source)	Tidal range (m)	Lowest survivors (m, MLW)
Snow's Cut, N.C. (Woodhouse, Seneca, and Broome, 1972)	1.2	0.2
Cold Springs Harbor, N.Y. (Johnson and York, 1915)	2.4	0.5
Romney Marsh, Mass. (Chapman, 1940)	2.8	0.9
Barnstable Marsh, Mass. (Redfield, 1972)	2.9	1.1

wind setup, this relationship may not hold. However, in general, smooth cordgrass can be established from just above MLW to MHW in areas with a tidal range of less than about 2.0 meters. In areas where tidal amplitude exceeds 2.0 meters, the lower limit or the planting zone is more restricted. In the north Atlantic where tidal amplitude may reach or exceed 3.0 meters, the plants are restricted to the upper one-half of the tidal zone. Observations of stable natural marshes in the vicinity of the proposed planting will generally provide reliable estimates of suitable planting zones.

d. Planting Density. On sheltered sites, a spacing of 1.0 meter will, under average conditions, provide complete cover by early spring of the second growing season. A 1-meter spacing is a density of about 10,000 propagules per hectare. On sites exposed to waves, a closer spacing of 0.5 meter is required. A spacing of 0.5 meter quadruples the density to about 40,000 propagules per hectare.

e. Planting Width. On sheltered sites, no minimum planting width (landward to seaward) is necessary. On sites exposed to waves, a practical minimum width is about 6.0 meters. However, at least 60 percent of the intertidal zone should be planted. If the planting area is not wide enough, the beach face must be graded to provide a suitable planting width. Grading must be well in advance of planting to allow for consolidation of the disturbed soil.

f. Planting Date. Smooth cordgrass can be planted year round but early spring planting avoids the winter storms and provides a longer growing season for plant establishment. A late spring and early summer planting may lessen the storm hazard but provide too little time for full plant establishment, particularly in the more northern latitudes. March, April, and early May probably represent the optimum planting season along the mid-Atlantic coast with the season starting somewhat later and becoming shorter northward. The practical planting season starts as early as February and extends much longer in the more southern extremes. Midsummer plantings have been successful on sheltered sites along the gulf coast.

g. Fertilization Requirements. Fertilization is recommended for all shore stabilization plantings except where previous experience has shown it to be unneeded.

Apply 1 to 3 kilonewtons of nitrogen (N) and 1 kilonewton of phosphate (P_2O_5) per hectare from soluble sources (ammonium sulfate and concentrated superphosphate, or diammonium phosphate) or in slow-release materials such as osmocote or mag-amp (see Sec. V for details on types, placement, application rates, and maintenance of fertilizer).

h. Planting Maintenance. Litter such as wood, styrofoam, algae, and dislodged submerged plants may accumulate in the planting areas and form a debris line. This material will smother and damage plantings particularly during the first two growing seasons. The debris should be removed in both the fall and spring.

Canada and Snow geese are fond of the tender roots and rhizomes of marsh plants and may destroy a planted area before the plants are well established in areas of high winter waterfowl concentrations. Rope fences erected on the seaward edge of planted areas (Fig. 23) have been used successfully to exclude waterfowl during the first few growing seasons. The fences consist of wood, metal, or plastic pickets strung with nylon rope, spaced at 15-centimeter intervals from the sediment surface to the high tide level (Garbisch, personal communication, 1977).

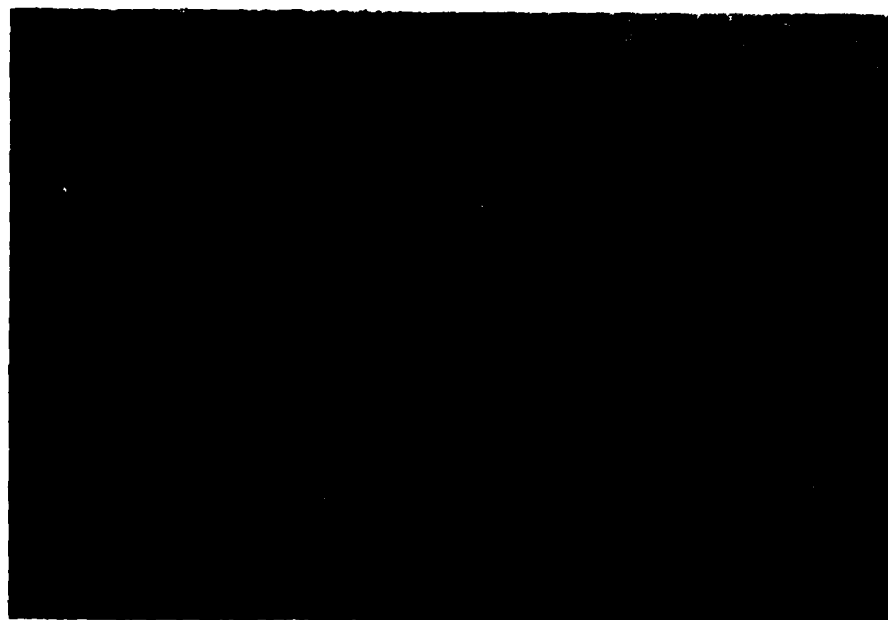


Figure 23. Nylon rope fence around smooth cordgrass planting.

Severe storms may cause damage to plantings particularly during the establishment period. Damage areas should be replanted.

1. Summary.

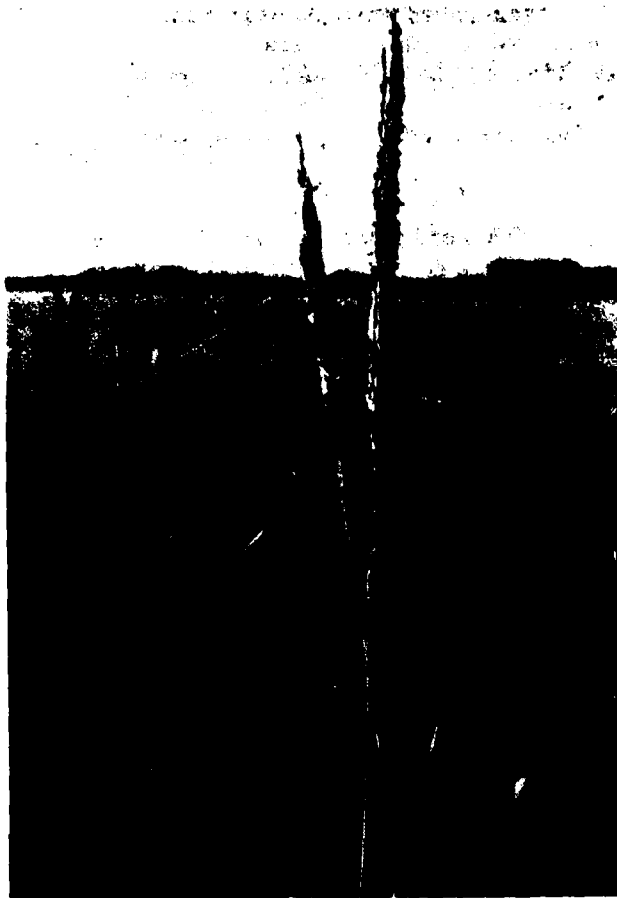
- (1) Plant types - sprigs, pot-grown seedlings, or plugs.
- (2) Plant spacing - 1.0 meter on sheltered sites (10,000 propagules per hectare); 0.5 meter on exposed sites (40,000 propagules per hectare).
- (3) Minimum planting width - no minimum on sheltered sites; for exposed sites 6.0 meters or 60 percent of the intertidal zone, whichever is larger.
- (4) Planting zone - slightly above MLW to MHW where tidal range is less than 2.0 meters; mean tide level (MTL) to MHW where tidal range is greater than 2.0 meters.
- (5) Salinity range - 5 to 35 parts per thousand.
- (6) Optimal planting dates - northern range in April and May; Mid-Atlantic in March, April, and May; southern range in February, March, April, and May.
- (7) Fertilization - 1 to 3 kilonewtons of nitrogen (N) and 1 kilonewton of phosphate (P_2O_5) per hectare.

2. Pacific Cordgrass (*Spartina foliosa*), Southern Pacific Coast.

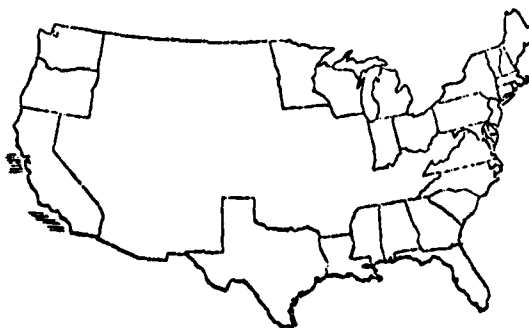
This grass is similar in appearance to the smooth cordgrass of the Atlantic and gulf coasts but does not grow quite as tall, is less vigorous, and is slower to establish. Pacific cordgrass (Fig. 24) is the dominant flowering plant in regularly flooded, intertidal marshes from Humboldt Bay southward to Mexico.

Pacific cordgrass is adapted to inundation and anaerobic soils through its oxygen transport system (Kasapliligil, 1976; Wong, 1976; Pride and Lingue, 1976). Hollow, air-filled tissue in the stem carries oxygen from the leaves to roots and rhizomes. This mechanism also introduces oxygen into the soil surrounding the root and rhizome system. The plant tolerates salt by excreting it through salt glands.

Two forms of Pacific cordgrass have been identified in San Francisco Bay: a medium, stout form (0.3 to 1.2 meters high) that grows in the lower zone, and a dwarf form (0.2 to 0.3 meter high) that occurs mixed with pickleweed at higher elevations (Mason, 1976). It is not known whether these forms have a genetic basis or are due to environmental features. Short-term field tests suggest that the two forms react differently to elevation (Harvey, 1976). The dwarf form was more successful than the stout form when transplanted in higher zones. A particularly stout, woody form of Pacific cordgrass has been observed in the high intertidal zone in Humboldt Bay, California. It appears to be extremely resistant to wave action and was initially considered to be a species or variety separate from Pacific cordgrass. Gerrish (1979) found that the stout, woody form belongs to the same chromosomal population as Pacific cordgrass.



a. Seed head (inflorescence)



b. Distribution (shaded area)

Figure 24. Pacific cordgrass.

Reproduction in established stands of Pacific cordgrass is vegetative through extensive underground stems (rhizomes). Although seed production is erratic and usually limited in old, dense stands, it may be substantial in newly established stands or along the margins of older stands. Seeds are important for spreading the plant into new or freshly disturbed areas (Mason, 1976).

The capacity of Pacific cordgrass to grow lower in the tidal zone than any other marsh species on the Pacific coast makes it especially valuable for shore stabilization.

a. Planting Techniques.

(1) Sprigs. Sprigs are the least expensive plant material and are the easiest to plant. A sprig consists of at least one node (joint of a stem from which leaves arise) with attached stems and roots. Sprigs are obtained from existing marshes. Field nurseries can be established as a source of plant materials, an early Pacific coast planting (Knutson, 1976) is now in use as a field nursery. In sandy substrates individual clumps may be loosened with a shovel, lifted, and separated into individual sprigs; however, the task is very laborious and likely to produce poor-quality plants in fine-grained sediments. In this case, plugs must be dug from the marsh and the individual sprigs separated with the use of a knife or other implement. In sandy sediments the highest quality transplants can be obtained from uncrowded stands which do not have a dense root mat. However, areas where Pacific cordgrass can be harvested on sandy sediments are rare. Because the natural spread of Pacific cordgrass is relatively slow, no more than 10 percent of the harvest area should be disturbed. Transplants may be hand-planted by inserting them 10 to 15 centimeters deep in holes opened by a dibble or shovel. In saturated fine-grained sediments the transplants may often be inserted without the use of implements. The soil around plants should be firmed to prevent "float out." Planting is generally feasible only during low water when the substrate surface is exposed.

(2) Pot-Grown Nursery Seedlings. Nursery seedlings are plants grown from seed in peat moss or plastic pots under controlled conditions. Three- to four-month-old seedlings are an alternative to sprigs. Five- to seven-month-old seedlings may be preferable to sprigs particularly if transplanted late in the growing season. Pot-grown seedlings are relatively easy to produce but considerably more expensive than sprigs (Fig. 25).

To prepare seedlings, seeds must be harvested from existing stands of Pacific cordgrass (Fig. 26). Seed production in Pacific cordgrass is very erratic. Early investigators believed that viable seeds were seldom produced and of minor significance in the spread of this species (Purer, 1942; Hinde, 1954). However, substantial seed crops (viability 80 percent) have been found in the San Francisco Bay area. Seeds from these sites have been harvested and stored, and plants have been produced from them (Mason, 1976). The best seed production was located near tributaries to the bay. The lower salinities at these sites may be a factor encouraging seed formation although this has not been established. Like smooth cordgrass, Pacific cordgrass seed heads may be attacked by ergot.



Figure 25. Pot-grown nursery seedlings (San Francisco Bay Marine Research Center, Inc., California).



Figure 26. Harvesting Pacific cordgrass seed.

Pacific cordgrass seeds mature in the San Francisco Bay area in October; seed heads begin to shatter shortly thereafter. Harvesting must be timed just before shattering when seeds are easily dislodged by tapping the heads or stalks. Mature heads may be harvested by hand either from a boat or by wading. Seeds should be stored in cold saltwater for about 2 weeks to loosen inflorescences. Seeds may then be threshed by placing the heads on a No. 30 screen and subjecting them to a strong spray of water from a hose. Viability of seeds is maintained over winter by storing in cold (4° Celsius) freshwater or saltwater (11 to 12 parts per thousand). Saltwater is more effective in preventing germination during storage. Mason (1976) found that satisfactory germination resulted when seeds were placed in freshwater at the end of the storage period. The germination of Pacific cordgrass may be more sensitive to salinity than smooth cordgrass. Viability is not maintained by drying or freezing. Seedling production procedures are the same as for smooth cordgrass. Though 5- to 7-month-old seedlings of Pacific cordgrass have not been tested, it is reasonable to assume that they would perform in a manner similar to smooth cordgrass seedlings.

The seeds are removed from storage and scattered over the surface of 5- to 10-centimeter pots filled with sand (seeds may be germinated in flats and transplanted into pots). Approximately 10 seeds are applied to the surface of each pot and covered with a thin layer of sand. The pots are then irrigated with tapwater and 10-10-10 fertilizer is applied after the seeds have germinated (0.25 to 0.50 kilonewton per hectare or 25 to 50 pounds per acre) and as often thereafter as needed to maintain good color and growth or slow-release materials may be mixed in the pot. If the seedlings are to be transplanted in a site where salinity is above 15 parts per thousand the solution should be adjusted with sodium chloride to maintain a salinity comparable to the site (Garbisch, 1977a, 1977b).

In saturated, fine-grained sediments, the potted seedlings can be inserted into the sediment without the assistance of a shovel or other implement. In sand substrates holes can be opened with a shovel, dibble, or mechanical auger. Pots should be set slightly below the substrate surface and soil firmed tightly around them.

(3) Plugs. A plug is root-soil mass, 10 to 15 centimeters in diameter and 15 to 20 centimeters deep, which contains roots and a number of stems. Plugs can be used as an alternative to sprigs or nursery seedlings. Plugs are much more expensive than sprigs. However, on the Pacific coast it is often difficult to locate uncrowded stands of cordgrass from which good quality sprigs can be obtained. Consequently, plugs may be used more frequently in this region than in other areas. Plugs are harvested from existing marshes which have heavy-textured sediments (Knutson, 1976). An intact root-soil mass cannot be maintained if plugs are excavated from noncohesive, sandy sediments. Similar to potted seedlings, plugs should be planted slightly below the substrate surface and soil firmed tightly around them.

Studies (Newcombe, et al., 1979) in San Francisco Bay have demonstrated the effectiveness of a new type of plug. It has been observed for some time that Pacific cordgrass growing in association with mussels (*Ischadium demissum* Dillwyn) form a ripraplike mat which is extremely resistant to wave energy (Pestrong, 1972). Newcombe, et al. (1979) harvested plugs from these mats and

used them to plant several eroding shore sites. They found these cordgrass-mussel plugs (termed "bioconstructs") to be more tolerant to wave activity than other plugs (Fig. 27). Locating a harvestable source for this type of plug will be considerably more difficult; however, where available, bioconstructs are advantageous.

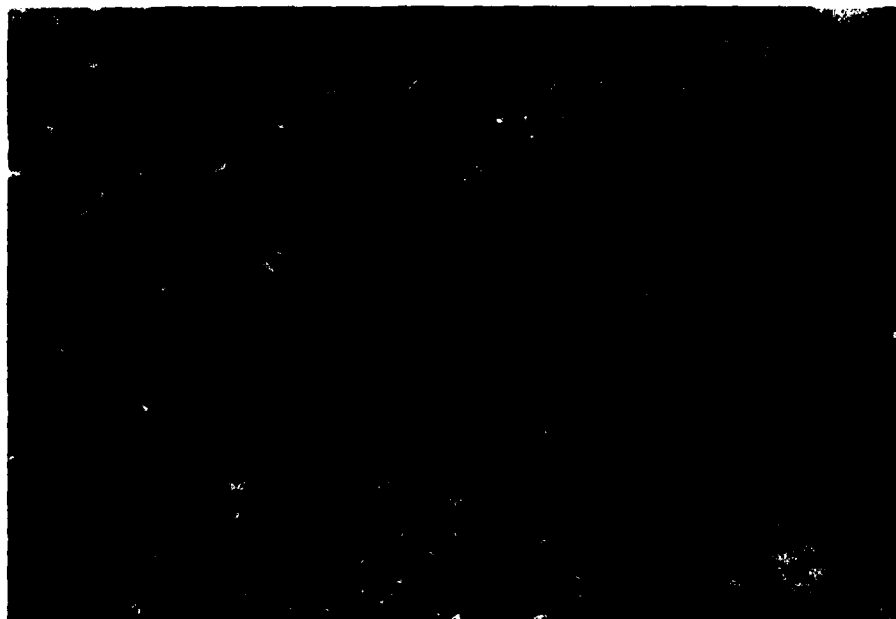


Figure 27. Cordgrass-mussel plugs of Pacific cordgrass.

b. Soils and Salinity. Pacific cordgrass can be established in either sand or fine-grained sediments. However, it is more likely to be nutrient-limited in sandy substrates (Barko, et al., 1977). Purer (1942) observed cordgrass in saline environments from 22 to 30 parts per thousand. Floyd and Newcombe (1976) found germination rates higher in freshwater than in salinities of 10, 20, and 30 parts per thousand. Phleger (1971) subjected adult Pacific cordgrass plants to salt solutions of 0 to 40 parts per thousand and found that growth was best in freshwater. However, the Phleger experiment lasted only 8 weeks and should not be considered conclusive. The transplanted adult plants certainly began the experiment with an accumulation of salt in plant tissues. In general, plantings are not likely to be effective when used in saline environments much above 35 parts per thousand.

c. Planting Zone. Submergence by the tides is probably the most important environmental factor affecting the distribution of intertidal plants. Pacific cordgrass is remarkably well adapted to withstand long periods of inundation. Most plants exchange gasses (breath) through small openings in their leaves known as stomata (from Greek meaning "mouth"). In Pacific cordgrass the stomata are sunken, and the "liplike" guard cells which surround the stomata are accompanied by subsidiary cells equipped with branched papilla (tiny fingerlike projections). It is speculated that these papilla trap air bubbles and prevent the wetting of the stomatal apparatus during submergence (Kasapliligil, 1976). Like several other members of the genus *Spartina*, smooth

and Pacific cordgrasses contain large airspaces within their shoots and roots. These airspaces (paerenchyma tissue) allow the plant to store its own supply of oxygen for respiration during submergence (Johnson and York, 1915; Purer, 1942). Experiments have also demonstrated that oxygen is transported downward through these tissues to the plants subsurface roots and rhizomes (Teal and Kanwisher, 1966; Wong, 1976). This adaption may allow the lower parts of the plant to carry on respiration and exchange of gasses via the emergent stems even when the plant is partially submerged. Because of this special adaptation, cordgrass survives lower in the intertidal zone than any other emergent plant in its range.

Table 3 summarizes some observations of Pacific cordgrass survival in low areas of the Pacific coast.

Table 3. Pacific cordgrass survival in lower intertidal zone (Rowntree, 1973).

Location	Tidal range (m)	Lowest survivors (m, MLLW)
Bolinas Lagoon, Marin County	1.4	0.6
Alameda Beach, near Bay Farm Island	2.0	0.8
Palo Alto Marsh, near Palo Alto Yacht Harbor	2.8	1.3

For all practical purposes, shore stabilization efforts on the Pacific coast can use MTL or slightly below as the lower boundary of the planting zone.

d. Planting Density. Pacific cordgrass spreads somewhat slower than its Atlantic coast counterpart, smooth cordgrass. Consequently, all stabilization projects should use a spacing of 0.5 meter. A 0.5-meter spacing is a density of about 40,000 propagules per hectare.

e. Planting Width. On sheltered sites, no minimum planting width (landward to seaward) is necessary. On sites exposed to wave action, a practical minimum width is about 6.0 meters. However, at least 60 percent of the upper half of the intertidal zone should be planted. If based on the elevational range of Pacific cordgrass and the slope of the shore, the potential planting area is not 6.0 meters wide, the shore must be graded to provide a suitable planting width.

f. Planting Date. Morris and Newcombe (1978) transplanted from Pacific cordgrass at monthly intervals and concluded that growth was best from April to August. Early spring planting (April) is preferred for stabilization projects.

g. Fertilization Requirements. A fertilizer response has not been demonstrated for Pacific cordgrass on fine-textured substrates. However, because early development is critical, fertilization is recommended for all shore stabilization projects unless nutrients availability is certain.

Apply 1 to 3 kilonewtons of nitrogen (N) and 1 kilonewton of phosphate (P_2O_5) per hectare from soluble sources (ammonium sulfate and concentrated superphosphate, or diammonium phosphate) or in slow-release materials such as osmocote or mag-amp (see Sec. V for details on fertilization requirements).

h. Planting Maintenance. Litter such as wood, styrofoam, algae, and dislodged plants accumulate and form a debris line. This material may smother and damage plantings particularly during the first two growing seasons. The litter should be removed in both the fall and the spring. Areas within the planting that are damaged by storms should be replanted.

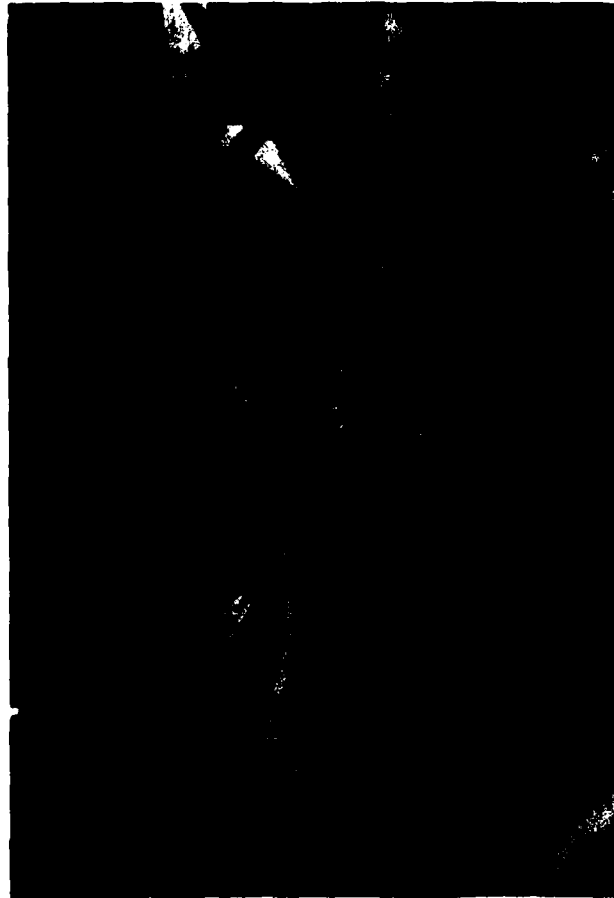
1. Summary.

- (1) Plant types - sprigs, pot-grown seedlings, or plugs.
- (2) Plant spacing - 0.5 meter (40,000 propagules per hectare).
- (3) Minimum planting width - no minimum width on sheltered sites; for exposed sites 6.0 meters or 60 percent of the upper one-half of the intertidal zone, whichever is larger.
- (4) Salinity range - less than 35 parts per thousand.
- (5) Planting zone - MTL to mean lower high water (MLHW).
- (6) Optimal planting date - April.
- (7) Fertilization - 1 to 3 kilonewtons of nitrogen (N) and 1 kilonewton of phosphate (P_2O_5) per hectare.

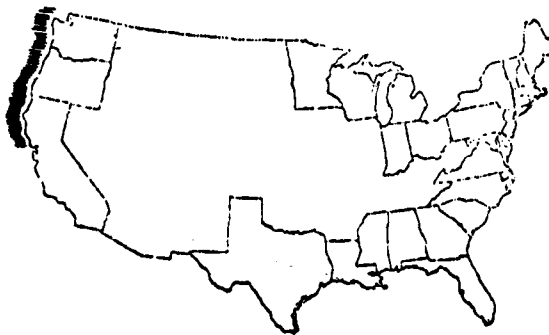
3. Pacific Northwest.

Few of the relatively large variety of plants found in marshes along this coast presently offer promise for planting purposes. More will probably be found useful with further experience. There is no single species such as Pacific cordgrass on the south Pacific and smooth cordgrass on the Atlantic and gulf coasts colonizing and dominating the lowermost, regularly flooded zone of salt marsh vegetation in this region. Jefferson (1975) identifies four species--Lyngbye's sedge, seaside arrowgrass, pickleweed, and tufted hairgrass--as the most important in trapping sediments along the Oregon coast. Of these four species, Lyngbye's sedge appears to be the most promising plant for use in erosion control.

a. Lyngbye's Sedge (*Carex lyngbyei*). This plant is a major component of salt, brackish and fresh water marshes in the northern Pacific coast (Fig. 28). The species composition of these northern marshes is more diverse than that found in other coastal areas of the United States. Also, less discrete elevation zones of vegetation are found in the less saline marshes of the northern Pacific, with a gradual change southward to the southern Pacific coast section between Humboldt Bay and San Francisco (MacDonald and Barbour, 1974). Little guidance is available for planting in the northern region. Successful intertidal plantings have been made in the Columbia River estuary



a. Seed head (inflorescence)
(photo courtesy of D.L. Higley and R.L. Holton)



b. Distribution (shaded area)

Figure 28. Lyngbye's sedge.

under freshwater conditions (Ternyik, 1977 and 1978). There have been several other smaller plantings in brackish water or saltwater (Armstrong, U.S. Army Engineer District, Seattle, personal communication, 1979).

(1) Planting Techniques. This plant spreads vegetatively and by seeds. Planting has been limited to sprigs gathered from the wild. This appears to be both satisfactory and practical for small to moderate plantings. Sedge is plentiful throughout most of the Pacific Northwest and it is easy to dig and transplant (Ternyik, 1977). Plants should be from young stands that are less than 2 years old and should consist of three or more stems. Preliminary tests using plugs have not been encouraging. It is likely that planting stock can be readily moved from high to low salinity sites but not from low to high. Good quality planting stock may be readily produced from older stands by covering them with 10 to 15 centimeters of sediment the year before the plants are to be used. As a large amount of this species is present in the region, this may often be more feasible than planting nurseries. Although sedge has been planted only by hand it should work well with planting machines.

(2) Soils and Salinity. Sedge marshes usually occur on silty substrates (Jefferson, 1973); however, the species can be planted in either coarse- or fine-grained substrates. Lyngbye's sedge will tolerate salinities in a range up to 20 parts per thousand.

(3) Planting Zone. Sedge should be planted from MLHW to mean higher high water (MHHW). In areas where tidal range is restricted (less than 2 meters) planting may be successful down to MTL.

(4) Planting Density. Transplants should be planted on 0.5-meter centers. This is a density of about 40,000 plants per hectare.

(5) Planting Width. On sheltered sites no minimum width (landward to seaward) is required. Minimum planting width should be at least 6 meters on sites exposed to wave action. If the planting zone is not 6 meters wide, the shore should be graded to provide a suitable planting width.

(6) Planting Date. April through June appears to be the preferred time for transplanting.

(7) Fertilization Requirements. Sedge was reported as very responsive to fertilization on a sandy substrate in the lower Columbia River, with little or no growth in unfertilized plots (Ternyik, 1977). This plant will probably respond to nitrogen and phosphorus under deficient conditions in about the same way as smooth cordgrass, and fertilization is likely to promote rapid establishment (see Sec. V for more details on fertilization requirements).

(8) Planting Maintenance. Tidal debris is a problem on many sites in this region, and care should be taken to prevent smothering of new plantings where heavy deposition of wood or debris occurs. Storm damage should be repaired by replanting.

(9) Summary.

(a) Planting technique - sprigs.

(b) Plant spacing - 0.5 meter (40,000 per hectare).

(c) Minimum width of planting - no minimum width for sheltered sites; sites exposed to waves should be planted to a width of at least 6.0 meters.

(d) Salinity range - 0 to 20 parts per thousand.

(e) Elevation - MLHW to MHHW.

(f) Optimal planting period - April, May, and June.

(g) Fertilization - 1 to 3 kilonewtons of nitrogen (N) and 1 kilonewton of phosphate (P_2O_5) per hectare.

b. Tufted Hairgrass (*Deschampsia caespitosa*). Experience with planting this species is limited, but it has been planted successfully. It is easy to transplant, quick to establish, and widely distributed in the Pacific Northwest (Fig. 29).

(1) Planting Techniques. Plantings have been done using material gathered from the wild (Ternyik, 1977). As tufted hairgrass is plentiful throughout the region and easy to dig, wild plants will probably be an adequate source for small projects. Tufted hairgrass has only been planted by hand, 10 to 12 centimeters deep. Some planting machines could be adapted to handle it. The grass should be relatively easy to propagate under nursery conditions because it grows readily above the normal tidal range. A nursery procedure similar to that described for smooth cordgrass is suggested. Transplants should probably be multistemmed.

(2) Soils and Salinity. Tufted hairgrass can be planted in both coarse- and fine-grained sediments and in fresh and brackish waters.

(3) Planting Zone. Natural range is from about MLHW upward. When planted with Lyngbye's sedge the two species should overlap at the elevation of MHHW and the tufted hairgrass should be extended somewhat higher than the sedge.

(4) Planting Density. 1.0-meter spacing.

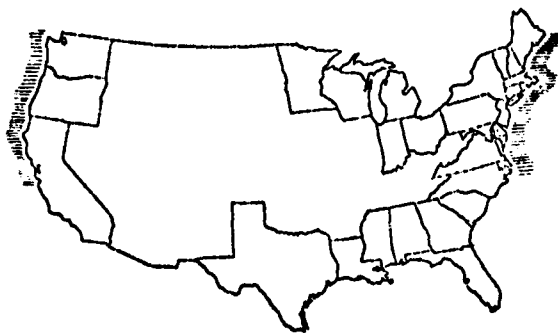
(5) Planting Width. No minimum.

(6) Planting Date. Based on behavior of similar species, April or May appears to be the best time to plant this grass.

(7) Fertilizer Requirements. There was some indication of fertilizer response on sandy substrate in the lower Columbia River, but it was not as striking as on sedge (Ternyik, 1977). Fertilizers (nitrogen and phosphorus) should be tried on this species where nutrient deficiencies are suspected.



a. Seed head (inflorescence)
(photo courtesy of D.L. Higley and R.L. Holton)



b. Distribution (shaded area)

Figure 29. Tufted hairgrass.

(8) Planting Maintenance. Debris deposited by high tides is definitely a hazard to plantings of this grass on many sites in the Pacific Northwest. Regular inspection and removal should be practiced where wood or litter deposition is heavy. Tufted hairgrass is grazed by wildfowl which could interfere with establishment in concentration areas. Storm damage should be repaired by replanting damaged areas.

(9) Summary.

- (a) Planting type - sprigs.
- (b) Plant spacing - 1.0 meter (10,000 per hectare).
- (c) Minimum width of planting - none.
- (d) Salinity range - fresh and brackish water.
- (e) Elevation - MHHW and above.
- (f) Optimal planting period - April, May, and June.
- (g) Fertilization - may be necessary in nutrient-poor sediment.

VII. PLANTING SPECIFICATIONS FOR OTHER USEFUL SPECIES

In general, the previously described primary species are effective pioneers in the intertidal zone. Once established they provide an environment to which many other species will invade over time. However, there are specific instances when incorporating additional species into the initial planting may be warranted. The additional species potentially useful for shore stabilization plantings include black needle rush, common reed, cordgrasses (big, gulf, and saltmeadow), mangroves (red, black, and white), saltgrass, seaside arrowgrass, and siltgrass.

1. Black Needle Rush (*Juncus roemerianus*).

This plant is an important and extensively occurring high marsh species along the Atlantic and gulf coasts. Success in transplanting this species has been erratic. Plants from young, uncrowded stands are definitely preferable to older plants. Seeds may germinate as soon as shed. They require direct sunlight and constant wetness. Black needle rush seeds are more difficult to harvest than seeds of the cordgrasses. Plantable seedlings have been produced in peat pots (Garbisch, Woller, and McCallum, 1975) and plastic containers (Broome, North Carolina State University at Raleigh, personal communication, 1980) but take more time and are more erratic than the cordgrasses. In light of the difficulties encountered in direct establishment of this species and the propensity it has for invading stands of other marsh plants after stabilization, direct planting of black needle rush as the primary species is rarely justified. Growth and spread is extremely slow, probably about 10 centimeters per year (Fig. 30). It is much easier to stabilize the area with smooth cordgrass, saltmeadow cordgrass, or big cordgrass and allow black needle rush to invade naturally where it is best adapted. If large grass plantings are



Figure 30. Seven years growth from single sprig of black needle rush (darker clump in right center), CERC Field Research Facility, Duck, North Carolina.

isolated from natural stands, it may be advisable to include 1 to 5 percent black needle rush in the initial planting to ensure the presence of a seed supply. Seeds mature in late spring or early summer. Fall planting might be considered for protected sites.

a. Planting Techniques. Transplants or potted seedlings.

b. Soil and Salinity. Silty clays, sand, and loams; 0 to 25 parts per thousand salinity (Kadlec and Wentz, 1974), but infrequently occurring in freshwater marshes (U.S. Army Engineer Waterways Experiment Station, 1978).

c. Planting Zone. MHW to extreme highest tide (varies from this where water levels are wind-controlled).

d. Planting Density. 1- to 4-meter spacing.

e. Planting Width. No minimum.

f. Planting Date. Spring.

g. Fertilization Requirements. 0.3 to 0.5 kilonewton of nitrogen (N) and phosphate (P_2O_5) per hectare from soluble sources 2 to 4 weeks after planting.

2. Common Reed (*Phragmites communis*).

This perennial grass is widespread throughout the United States especially in the northwest and east. It is an aggressive, weedy plant which often

crowds out more desirable plant species (Ward, 1942). Figure 31 shows a successful planting for erosion control. In the Great Lakes, common reed is the most promising plant for erosion control (Woodhouse, 1979).



Figure 31. Erosion control planting with common reed, CERC Field Research Facility, Duck, North Carolina.

- a. Planting Techniques. Hand or machine plant, upright, leaving a few centimeters exposed. Plant only when soil is moist.
- b. Soil and Salinity. Common reed may be planted in either coarse- or fine-grained sediments and will withstand salinities up to about 20 parts per thousand (U.S. Army Engineer Waterways Experiment Station, 1978).
- c. Planting Zone. Will withstand drought but requires shallow flooding in spring (U.S. Army Engineer Waterways Experiment Station, 1978). Will not tolerate permanent flooding of depths greater than 15 centimeters (Ward, 1942).
- d. Planting Density. 0.5-meter spacing.
- e. Planting Width. 6.0 meters.
- f. Planting Date. Spring.
- g. Fertilization Requirements. 0.3 to 0.5 kilonewtons of nitrogen (N) and phosphate (P_2O_5) per hectare from soluble sources 2 to 4 weeks after planting. Fertilization will seldom be warranted because of common reed's aggressive nature.

3. Cordgrasses.

a. Big Cordgrass (*Spartina cynosuroides*). This cordgrass occurs extensively along the Atlantic and gulf coasts wherever freshwater influence is strong, along tidal creeks and in brackish waters such as Currituck Sound, North Carolina, and large areas in the Mississippi Delta where it, together with common reed, make up the "cane zone." It is a vigorous grower, larger and taller than smooth cordgrass and forms a dense root-rhizome mass affording excellent protection in its zone of adaptation. Big cordgrass has very specific elevation and flooding requirements which limit it to a rather narrow zone from about MHW upward, often in a narrow band between smooth and saltmeadow cordgrass zones. It is especially easy to grow in pots. Seeds germinate readily and seedlings grow rapidly. Seeds should be stored in cold saltwater, 10 parts per thousand. It can be used very effectively in brackish areas just above smooth cordgrass.

Plant production, transplanting, spacing and management are the same as described for smooth cordgrass in Section VI.

b. Saltmeadow Cordgrass (*Spartina patens*). Saltmeadow cordgrass is a fine-leaved grass, 15 to 90 centimeters high, that occurs extensively in the occasionally flooded high marsh zone all along the Atlantic and much of the gulf coasts (Fig. 32). In the absence of black needle rush, it replaces smooth cordgrass at about the MHW level and forms dense mats from MHW to the high spring or storm surge line. This grass forms a narrow band along the marsh edge but on gently sloping topography it may cover a wide expanse and be mixed with saltgrass, patches of black needle rush, and other high marsh species. Saltmeadow cordgrass forms the extensive saltmeadows of New England that were formerly mown for hay.

Saltmeadow cordgrass can withstand extended periods of both flooding and drought, and often occurs where surface drainage is poor, causing ponding of rainwater during wet periods. It cannot tolerate the daily flooding of the intertidal zone. Saltmeadow cordgrass is a valuable stabilizer for the zone between the smooth cordgrass and the high spring or storm surge line. This zone is not exposed to direct attack by waves except when storms cause higher than normal water levels. Even on eroding shorelines this zone will often have complete vegetative cover and will not require planting. However, if the zone is unvegetated, planting of saltmeadow cordgrass will retard erosion from surface runoff (Fig. 33).

(1) Planting Techniques.

(a) Sprigs. Saltmeadow cordgrass is plentiful in high marshes and on low sandflats along the Atlantic and gulf coasts, but it is difficult to obtain good planting stock from the wild. Stands on moist sites soon become so dense that harvesting is difficult, and the crowded plants do not make vigorous planting stock. Plants growing on dry, infertile sites lose vigor and survive poorly when transplanted. The best transplants are the large culms from rapidly growing, uncrowded young stands; however, obtaining significant quantities of this kind of transplant may require the establishment of a nursery. Although saltmeadow cordgrass is also found in coastal



Figure 32. Saltmeadow cordgrass meadow (Maine) (photo courtesy of Steven Leatherman).



Figure 33. Saltmeadow cordgrass planted landward of smooth cordgrass (photo courtesy of E.W. Garbisch).

swales and dunes, planting stock should not be obtained from these areas. Recent evidence indicates that there is adaptive genetic divergence among the marsh swale and dune subpopulations of saltmeadow cordgrass (Silander, 1979).

Saltmeadow cordgrass can be grown as readily inland as on the coast. However, survival of such material has been variable when transplanted to more saline environments. It should be planted on a weed-free, sandy soil with a moderately good moisture-holding capacity. The seedbed should be well pulverized, and if needed, fumigated with methyl bromide to kill weed seeds. Seed may be used for nursery establishment but transplants are usually more practical. Nursery plantings should be made in late winter or spring. One- to three-culm transplants should be used from young, vigorous stands set 10 to 15 centimeters deep in moist soil, 0.5 meter apart in rows. To allow cultivation, rows should be spaced about 1 meter apart. Fertilizing should be done at planting; topdress with nitrogen later if needed as indicated by growth and appearance.

It is usually best to harvest nursery-grown stock after one growing season to avoid the development of overcrowded, less desirable plants. Harvest is accomplished by loosening individual clumps with a shovel, a tree digger, or a similar tool and then lifting. Saltmeadow cordgrass culms are small even under the best growing conditions; clumps should be divided into four- to eight-culm plants for transplanting. Plants may be stacked upright in tubs, baskets, or crates for handling and transport, or bundled in the same way as tree seedlings. Care must be taken to avoid drying or heating. Plants may be heeled in moist sand for temporary storage.

Field-grown plants may be planted by hand by inserting them 15 to 20 centimeters deep in holes opened with a dibble or shovel or in furrows opened by machine. Soil should be firmed around them to minimize blowouts and washouts. Tobacco or strawberry planters can be modified to handle them. Soil should always be moist at planting.

(b) Pot-Grown Nursery Seedlings. Nursery seedlings are an alternative to the use of sprigs for the planting of saltmeadow cordgrass; however, seedlings are more expensive. Seedlings will be preferable where salt buildup or drought is likely to interfere with initial establishment. The more intact root systems of the pot-grown seedlings provide better plant survival. Salt buildup is likely in part of the saltmeadow cordgrass zone when inundation by spring tide or storm surges is followed by periods of low rainfall and warm temperatures. Established plants can tolerate this but fresh transplants may suffer severe damage.

To prepare seedlings, seeds must be harvested from existing stands of saltmeadow cordgrass. Saltmeadow cordgrass is a fairly consistent seed producer. It grows on irregularly flooded and unflooded sites and the seeds do not require moist storage (Webb and Dodd, 1976). Large-scale harvesting and processing of this species could be handled with the same equipment and in a similar manner as many of the cultivated grasses. Small quantities are harvested by hand, as with smooth cordgrass. Seed should be stored dry. Storage at low temperature is probably best, although there is no clear-cut evidence to support this. The seeds should be removed from storage and scattered over the surface of 5- to 10-centimeter plastic or peat pots filled with sand about 3 or 4 months before transplanting time (seeds may be germinated in flats and

transplanted into pots). Approximately 10 viable seeds should be applied to the surface of each pot and covered lightly to imbed the seeds. The pots should be irrigated with tapwater and fertilized with 10-10-10 (0.3 to 0.5 kilonewtons per hectare) after the seeds have germinated or with slow-release material mixed in the pot. If the seedlings are to be transplanted in a site with salinity above 15 parts per thousand the solution should be adjusted with sodium chloride to maintain a salinity comparable to the proposed planting site (Garbisch, personal communication, 1977).

(2) Soils. Saltmeadow cordgrass can be planted in cohesive as well as sandy sediments.

(3) Planting Zones. Saltmeadow cordgrass exhibits an unusual reaction to elevation in that it grows lower into the tidal range from south to north. It is found only well above MHW in Georgia, but extending down into the upper 10 percent of the mean tidal range in Maine, and in an intermediate position on the Delaware coast (Reimold and Linthurst, 1977). On the gulf coast it can be established down to MHW (Webb, et al., 1978). Planting elevation for this species should either coincide with that of natural stands in the vicinity, or it should overlap a part of the planting zones for other species planted above and below it.

(4) Planting Density. On most sites planting on 1-meter centers is adequate for both sprigs and 15-week-old seedlings. This is a density of about 10,000 propagules per hectare. Density can be increased to 0.7- or 0.5-meter centers in critical situations.

(5) Planting Width. There is no recommended minimum planting width for this species. In general, within practical limits unvegetated areas adjacent to and above the smooth cordgrass planting should be planted. Plants are difficult to establish on the face of eroding banks unless the slope of the bank face is 1 to 5 or more gradual.

(6) Planting Date. Saltmeadow cordgrass has a rather wide tolerance to time of planting, from late winter to early summer; Gallagher, Plumley, and Wolf (1977) suggest fall planting, but this has not been tested. Late spring is probably the preferred time in most cases. However, where salt buildup is likely, earlier planting is essential. Soil moisture content during and following planting is probably more important for this species than planting date.

(7) Planting Management. Saltmeadow cordgrass is very responsive to fertilizers under nutrient-poor conditions. Response usually occurs on sandy or peaty substrates but occasionally extends to silts and clays. Under these conditions, fertilizer can be a useful and relatively inexpensive tool in promoting rapid establishment and resistance to wave stress. Where nutrient deficiency is expected, apply 0.3 to 0.5 kilonewton of nitrogen (N) and a similar amount of phosphate (P_2O_5) per hectare from soluble sources 2 to 4 weeks after planting or as soon as new growth appears. Follow at about 6-week intervals with a second and third application of nitrogen. Slow-release materials applied in the planting hole are very effective on this grass, particularly in compact soils. Soluble fertilizers should not be placed in the planting hole because of the risk of salt injury.

(8) Summary.

- (a) Planting technique - sprigs or 15-week-old seedlings.
- (b) Planting density - 1.0-meter spacing.
- (c) Minimum width - none.
- (d) Optimum salinity range - 10 to 35 parts per thousand.
- (e) Planting zone - north Atlantic, upper 10 percent of mean tidal range to extreme high tide; mid-Atlantic, MHW to extreme high tide; south Atlantic, above MHW to extreme high tide; gulf, MHW to extreme high tide.
- (f) Planting season - north Atlantic in April and May; mid-Atlantic in March, April, and May; south Atlantic and gulf in February, March, and April.
- (g) Fertilization requirements - 1.0 to 1.5 kilonewtons per hectare of nitrogen (N) and 1.0 kilonewton of phosphate (P_2O_5) divided into three applications.

c. Gulf Cordgrass (*Spartina spartinae*). Gulf cordgrass is a bunch-type grass somewhat resembling but readily distinguishable from saltmeadow cordgrass by its bunch habit (Fig. 34). Gulf cordgrass replaces saltmeadow cordgrass in heavy soils on the western Louisiana and Texas coasts. It occurs from MHW inland for a distance of more than 80 kilometers in moist upland clay sites. Because gulf cordgrass is seldom in direct contact with waves, it should not be used alone for shore stabilization. Plantings will generally reduce erosion due to runoff in clay sediments in the zone immediately above smooth cordgrass.

There has been little experience with planting gulf cordgrass. However, the plant should respond to the planting techniques used for saltmeadow cordgrass (Dodd and Webb, 1975).

4. Red Mangrove (*Rhizophora mangle*), Black Mangrove (*Avicennia germinans*), and White Mangrove (*Laguncularia racemosa*).

Three mangrove species occur along the Florida coast: the red mangrove, the black mangrove, and the white mangrove (Fig. 35). Red mangrove tolerates the deepest submersion, white mangrove the driest soil, and black mangrove the highest salinity. Black mangrove is the most cold-hardy but the slowest grower. White mangrove has the least cold tolerance and is the fastest growing (Davis, 1940; Savage, 1972; Pulver, 1976).

The red mangrove is well adapted to invade new areas through its large, viviparous seed (germinates within the pencil-like radicle while still attached to the tree), which is ready to take root as soon as it falls from the tree. Propagules remain viable while floating long distances for months and take root upon landing on a suitable site. This is usually the first mangrove to



Figure 34. Gulf cordgrass.

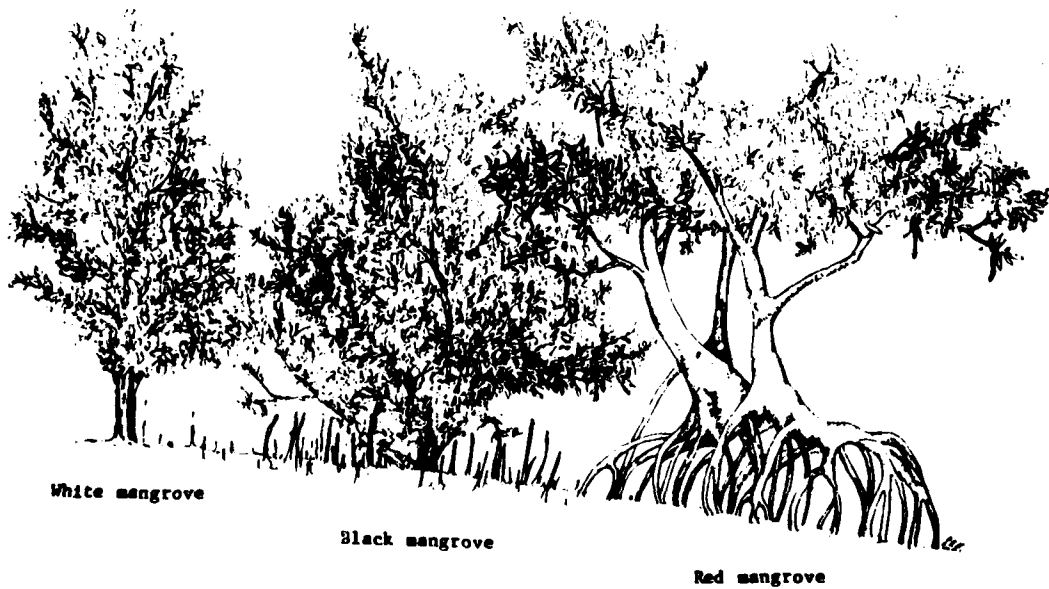


Figure 35. White, black, and red mangroves.

invade new areas and has been considered the chief agent for shoreline stabilization in Florida (Davis, 1940). The isopod parasite (*Spasromx terebrans*) causes serious damage to red mangrove roots on some sites (Teas, 1977).

Savage (1972) points out that black mangrove may be preferable for shore stabilization. It is more cold-hardy, more tolerant of artificial substrates and high-energy conditions, and provides earlier and more complete protection through the development of an accessory root system (pneumatophores) than the other two species. White mangroves appear to have the lowest value for stabilization because the seedlings have more fragile root systems and are very slow to develop accessory roots. It invades and coexists with the other two and contributes to stability in this way.

The red mangrove usually fringes the shoreline. Apparently, this species is able to establish at slightly lower water levels than the other two. Where both mangroves and salt marsh occur together, the mangroves extend seaward of the salt marsh. Mangroves, once established, can tolerate deeper water than salt marsh plants. Mangroves easily form hedges along developed waterfront property. Savage (1972) found that all three species respond well to selective pruning. Thus, they can be used to replace or protect bulkheads and still fit landscaping plans, and can be pruned to avoid visual obstruction. Mangroves play a role in stabilization and primary production similar to that of temperate zone salt marshes and are generally considered their subtropical and tropical equivalents.

Established mangroves are very effective stabilizers (Carlton, 1974). The black mangrove produces extensive accessory root systems that form dense mats in and above the soil surface. The red mangrove develops a system of prop roots which provides substantial trapping capacity. However, these tree species require considerably more time for complete establishment and are more difficult to establish on bare sites than are the grasses in the intertidal zone. Savage (1972) found that a minimum of 3 or 4 years is required for black mangrove seedlings to develop stabilizing roots; red mangrove seedlings require 5 or more years to develop prop roots. This can be cut in half by growing plants under controlled conditions (H. Teas, Botanist, University of Miami, Coral Gables, Florida, personal communication, 1978). Even so, this means a period of at least 2 to 3 years from planting of mangrove seeds or seedlings to stabilization, compared with 9 to 14 months for smooth cordgrass. Also, the slow development of mangrove seedlings makes them much more vulnerable to damage or disturbance from wave and tidal action, floating debris, traffic and browsing by animals and insects than most salt marsh species (Savage 1972; Teas, Jergens, and Kimball, 1975). The alternative of planting 4- to 8-year-old plants, which have a better chance of survival, would be expensive and appears to be impractical except in small-scale, special purpose plantings.

Fortunately, a natural sequence along many of these shores is the initial stabilization of newly exposed intertidal sites by smooth cordgrass, followed by the invasion of mangrove seedlings. The smooth cordgrass is gradually overcome and eliminated through shading as the mangroves develop into trees (Lewis and Dunstan, 1975, 1976). Evidently, the mangrove seedlings establish more easily after the substrate has been stabilized by the grass. The natural sequence of grass, followed by mangroves, offers a practical method of

establishing vegetative cover in the intertidal zone. Stabilization can be accomplished rapidly and at low cost by planting smooth cordgrass. This will be followed on most sites by the natural invasion and eventual takeover of mangroves, if there is an adequate seed supply. Planting of mangrove seed, seedlings, or plants in the cordgrass stand soon after stabilization would speed the transition, if desired.

a. Planting Techniques. Plants should be set in holes large enough to accommodate the root mass, at about the same level in the ground as they were growing, with the edges of the hole filled and firmed. This can be done best at low tide. The root ball should be kept intact and care taken not to cover pneumatophores or prop roots.

Watering is advisable at higher elevations where daily flooding does not occur. Pruning definitely improves survival and early growth. Black and white mangroves should have top and side branches pruned to about two-thirds of their original length. Pruning of red mangroves must be selective; lateral buds may not grow on branches pruned back to a diameter greater than 2.5 centimeters (Pulver, 1976).

b. Salinity. Tolerant to sea strength 35 parts per thousand.

c. Planting Zone. Established red mangroves tolerate continuous water coverage of the substrate surface 0.5 meter deep to occasional flooding a few centimeters deep. The black mangrove grows slightly higher, under a few centimeters of standing water to barely flooded by spring tides or storm surges. The white mangrove will grow with the other two at about all elevations (Davis, 1940). Successful plantings of all three species have generally been above MTL. Propagules and young plants cannot tolerate continuous flooding (Teas, 1977). It may be possible to succeed at lower elevations by using older plants.

d. Planting Density. Seedlings may be planted as close as 0.5 meter on centers and natural thinning permitted to determine the final stand. With the more expensive saplings, a 2- to 3-meter spacing is suggested.

e. Planting Width. No minimum.

f. Planting Date. The optimum planting season of young seedlings, dug from the wild, is in late February and March. Planting of larger plants can probably be done successfully throughout the year if done with care.

g. Fertilization Requirements. There are no data to support the use of fertilizers on mangrove planting. These species respond to fertilizer in nurseries (Teas, 1977) and will probably respond to the addition of nitrogen and phosphorus in the field on some sites. The cost of slow-release materials such as osmocote or mag-amp applied in the planting hole, would be warranted if needed, for the larger transplants. Fertilization should be tried wherever nutrient limitations are suspected.

h. Planting Management. Smothering by drifting debris is a problem on some sites, particularly with small plants. Removal of debris should be practiced during the period of establishment. Pruning of established plants may be continued where mangroves play an ornamental role. The black and white

species will tolerate severe selective pruning; the red should be pruned with care, cutting only branches smaller than 2.5 centimeters.

5. Saltgrass (*Distichlis spicata*).

Saltgrass is widely distributed in high marshes along the Atlantic, gulf and northern Pacific coasts and to a lesser extent along the southern Pacific coast. It is more salt tolerant than other high marsh species (Chabreck, 1972) and is often dominant in small, poorly drained, more saline patches. It has not been planted extensively. Hardisky and Reimold (1979) stated that this grass survived well, spread rapidly the first 2 years after transplanting, and was then gradually replaced by taller species. They suggest that it is a valuable plant for early stabilization of bare sites. It evidently warrants further attention.

6. Seaside Arrowgrass (*Triglochin maritima*).

This plant is a very plentiful pioneer in the northern Pacific coast. In most areas it will be found lower in the intertidal zone than either Lyngbye's sedge or tufted hairgrass. Seaside arrowgrass has been planted on a limited scale (J. Armstrong, U.S. Army Engineer District, Seattle, personal communication, 1979). Multiple-stemmed transplants or plugs are likely to be effective. Procedures should be similar to planting Lyngbye's sedge. When planted with sedge, the two species should overlap at MLHW and the arrowgrass should extend somewhat lower than the sedge.

7. Siltgrass (*Paspalum vaginatum*).

On the peninsula of Florida, this grass often occupies or shares with saltmeadow cordgrass the zone just above MHW normally reserved for saltmeadow cordgrass elsewhere. It spreads rapidly, is more drought resistant than the latter, and is easier to transplant under the frequently dry conditions occurring along those coasts. Propagation, transplanting, and management requirements appear to be very similar to those described for saltmeadow cordgrass.

VIII. COST

1. Cost Comparison with Other Erosion Control Methods.

Vegetative stabilization is the least costly of all erosion control measures. A 10-meter-wide (landward to seaward) shoreline planting requires an investment of only about \$12 per linear meter to hand plant sprigs and about \$28 per linear meter to hand plant nursery seedlings (based on labor costs of \$15 per hour plus 100 percent for overhead). Costs for structural alternatives will range from \$50 to \$1000 per linear meter. Figure 36 compares planting costs with four standard structural alternatives. In addition, planting does not require any specialized equipment and smaller projects can be undertaken by a crew of two to three people.

Because vegetative stabilization is cost effective, planting should often be attempted even when success is questionable.

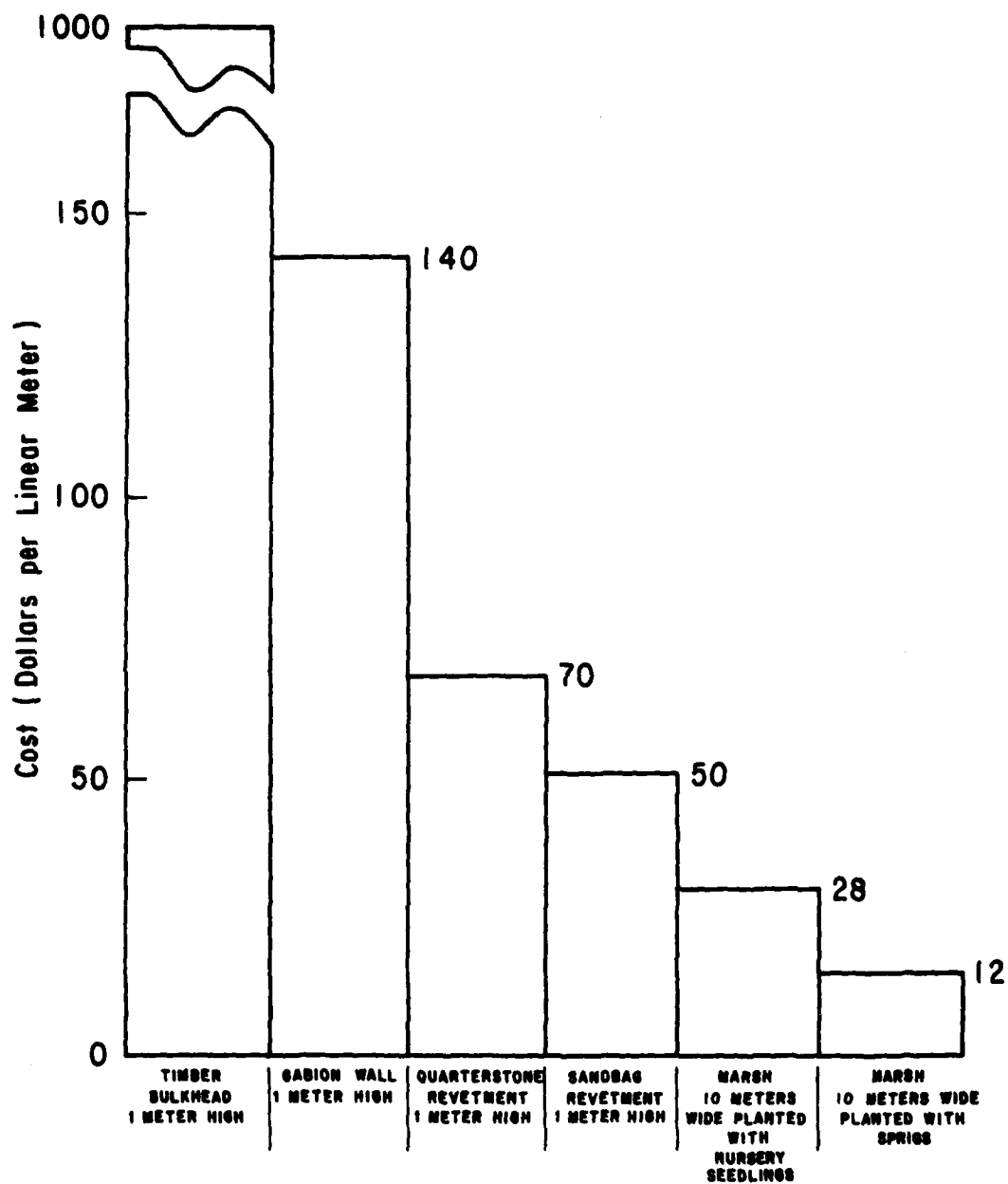


Figure 36. Cost comparison of various shore stabilization methods (dollars per linear meter).

2. Planting Costs.

a. Site Preparation. Sites which have little likelihood of being successfully stabilized can be modified to improve their suitability. The two primary methods of improving a site are: (1) grading of the beach face or (2) constructing a wave-stilling device.

(1) Grading the Beach Face. Grading the beach face can increase the width of the area available for planting and the distance over which wave energy will be dissipated. This will usually improve the chances for successful plant establishment. The following is an estimate of the costs required to create a 1 on 15 slope in front of a 1-meter-high bank (adapted from Eckert, Giles, and Smith, 1978):

<u>Method</u>	<u>Cost per cubic meter</u>	<u>Cost per linear meter</u>
Dredge (hydraulic placement)	\$4.50	\$33.75
Dump-truck placement	9.00	67.50

These values were calculated assuming: (a) there is easy access to the work site, (b) the fill material is within a reasonable distance to the work site, (c) all construction is in an area of low to moderate wave climate, (d) grading is included in the estimate, and (e) the hydraulic dredge is used for only large projects in excess of 1000 linear meters.

(2) Wave-Stilling Devices. Wave-stilling devices are used to protect the planting from severe wave impact. These can be very helpful in protecting plants through the critical establishment period. The following is an estimate of the cost of constructing two low-cost wave-stilling devices:

<u>Method</u>	<u>Cost per linear meter</u>
Rubber tire breakwater (two tires high, labor included ¹)	\$25 (adapted from Webb and Dodd, 1978)
Sandbag dike breakwater (1 meter high with filter cloth included)	\$100 (adapted from Eckert, Giles, and Smith, 1978)

¹Labor is estimated at \$30 per man-hour (\$15 per man-hour direct costs plus 100 percent overhead).

b. Harvesting, Processing, and Planting. The labor required to acquire or produce propagules and to plant is the principal cost of a project unless site preparation or temporary protection is required. Labor demands vary widely with species, availability of plants and seeds, type of propagule, accessibility of the site, soil type, size of operation, and degree of mechanization used. Working hours in the intertidal zone are controlled by tidal regimes. Both harvesting and planting are usually confined to about a 5-hour period per tide. This restriction requires careful coordination for efficient operation and often adds substantially to the cost.

Though the amount of labor necessary to harvest, process, and plant may vary widely from project to project, experience from previous studies is useful as a general guide to estimate labor requirements. Table 4 summarizes several estimates of labor requirements for various species and propagule types.

Table 4. Man-hours required to harvest, process, and plant 1,000 planting units.

Species-Operation	Plant materials		
	Sprigs	Seedlings	Plugs
Smooth cordgrass			
Harvest and process			
With plow	2.5 ¹	-	-
With backhoe	3.3 ¹	-	-
By hand	5.0 ¹	16.7 ²	-
Planting:			
With tractor	2.8 ¹	-	-
By hand	5.5 ¹	-	-
With power auger	-	6 ²	-
Pacific cordgrass			
Harvest and process	10.0 ³	49.0 ³	29.1 ³
Plant	22.0 ³	37.0 ³	57.0 ³
Lyngbye's sedge			
Harvest, process, and plant	9.6 ⁴	-	-
Tufted hairgrass			
Harvest, process, and plant	8.7 ⁴	-	-

¹Woodhouse, Seneca, and Broome (1974).

²Estimated from advertised costs of 3- to 4-month potted nursery seedling, Environmental Concern, Inc., 1979. Assumed labor to be \$15 per hour and overhead rate of 100 percent.

³U.S. Army Engineer District, San Francisco (1976) (cohesive sediments).

⁴U.S. Army Engineer Waterways Experiment Station (1978).

Smooth cordgrass sprigs can be harvested, processed, and planted by hand at a rate of about 10 man-hours per 1,000 plants. Sprigs of Lyngbye's sedge and tufted hairgrass can be planted at about the same rate. Sprigs of Pacific cordgrass appear to be more difficult to plant, as indicated in Table 4. However, the Pacific cordgrass planting (U.S. Army Engineer District, San Francisco, 1976) was done in cohesive sediments which greatly slowed the planting operations. The preparing and planting of nursery seedlings is more than twice as time consuming as using sprigs—about 23 man-hours per 1,000 planting units. Using plugs is at least three times more time consuming than sprigs.

c. Site Maintenance.

(1) Fertilizer. Conventional fertilizer costs (including materials and labor) are variable but will range from about \$150 to \$250 per hectare (1980 prices) (\$0.15 to \$0.25 per linear meter for a 10-meter width) the year of establishment. Slow-release fertilizer is considerably more expensive, about \$1,500 to \$2,500 per hectare (1980 prices) or \$1 to \$4 per linear meter for a 10-meter-wide planting.

(2) Debris Removal. Litter such as wood, styrofoam, algae, and dislodged submerged plants accumulate in the high marsh and form a debris line. This material may smother and damage plantings particularly during the first two growing seasons. This litter should be removed in both the fall and the spring. An estimate of labor required to perform this work is not available.

(3) Wildlife Predation. Canada and Snow geese are fond of the tender roots and rhizomes of marsh plants and may destroy plantings before establishment in areas near waterfowl wintering concentrations. Rope fences erected on the seaward edge of planted areas have been used successfully to exclude waterfowl during the first few growing seasons. The fences consist of wood, metal, or plastic pickets strung with nylon rope. The ropes are spaced at 15-centimeter intervals from the sediment surface to MHW (Garbisch, personal communication, 1977). Estimates for the cost of this work are not available.

3. Summary.

a. Cost Comparison:

(1) Vegetative stabilization (10-meter-wide, landward to seaward planting):

(a) Sprigs - \$12 per linear meter.

(b) Nursery seedlings - \$28 per linear meter.

(2) Sandbag revetment - \$50 per linear meter.

(3) Quarrystone revetment - \$70 per linear meter.

(4) Gabionwall - \$140 per linear meter.

(5) Wood sheeting bulkhead - \$1,000 per linear meter.

b. Planting Costs:

(1) Site preparation (as required):

(a) Grading - \$35 to \$70 per linear meter.

(b) Wave-stilling devices - \$25 to \$100 per linear meter.

(2) Planting operations (10-meter-wide, landward to seaward planting):

(a) Sprigs - \$12 per linear meter.

(b) Nursery seedlings - \$28 per linear meter.

(c) Plugs - \$35 per linear meter.

(3) Fertilization (10-meter-wide, landward to seaward planting):

(a) Soluble - \$0.15 to \$0.25 per linear meter.

(b) Slow-release - \$1 to \$4 per linear meter.

IX. IMPACT ASSESSMENT

1. Potential Benefits.

Salt marshes are valued as sources of primary production (energy), as nursery grounds for sport and commercial fishery species, and as a system for storing and recycling nutrients and pollutants such as nitrogen, phosphorus, and heavy metals. Once established, erosion control plantings function as natural salt marshes and gradually develop comparable animal populations (Cammen, 1976; Cammen, Seneca, and Copeland, 1976).

a. Marsh Ecology. Little of the biomass of salt marsh, about 5 percent, is consumed while the plant material is still living. Grasshoppers and plant hoppers graze on the grass and are, in turn, eaten by spiders and birds. Direct consumption of rhizomes and culms of marsh grasses by waterfowl may be significant locally near waterfowl wintering grounds. Periwinkles graze on algae growing on the grass. The majority of the energy is believed to move through the detrital food chain. Dead grass is broken down by bacteria in the surrounding waters and on the surface of the marsh. This process greatly decreases the total energy but increases the concentration of protein, thereby, increasing the food value. Some detrital particles and mud algae are eaten by a variety of detritus feeders such as fiddler crabs, snails, and mussels; these organisms are, in turn, eaten by mud crabs, rails, and raccoons. The remaining detritus, augmented by the dead matter from the primary and secondary consumers, is washed from the marsh by tidal action as new export. This exported detritus, with material from submergent aquatic plants and the plankton, feeds the myriad of larvae and mature fish and shellfish which use estuaries, bays, and adjoining shallow waters. Marsh grasses may account for most of the primary production of the system in waters where high turbidity reduces light penetration, thereby reducing phytoplankton and submergent aquatic production.

The productivity and utilization of high marsh has received less attention than that of low marsh. Indications are that net production of some high marsh may equal that of many low marshes. The important difference, however, is that the export mechanism of frequent tidal flushing is absent in high marsh. Consequently, much of the high marsh biomass goes into peat formation, in situ rather than into the estuarine food chain. For this reason, high marsh appears to be of much less direct value to the estuary.

The rigorous environment of the salt marsh sharply limits the number of animals living there. These areas are used by birds such as herons, rails, sandpipers, geese, ducks, and songbirds and by raccoons. A much larger population of animals lives in or on the mud surface. The more conspicuous are fiddler crabs, mussels, clams, and periwinkles. Less obvious but more numerous are annelid and oligochaete worms and insect larvae. In addition, larvae, juveniles, and adults of many shellfish and fish are commonly found in the marsh creeks.

Little is known of the animal populations and the feeding relationships in high marsh.

b. Nutrient Cycling. Salt marshes have substantial absorptive capacities for potential pollutants such as nitrogen, phosphorus, and heavy metals (Williams and Murdock, 1969; Woodhouse, Seneca, and Broome, 1974). Increased growth of salt marsh species, particularly smooth cordgrass, in response to nutrients has been noted at several locations (Valiela and Teal, 1974; Woodhouse, Seneca, and Broome, 1974; Garbisch, Woller, and McCallum, 1975; Patrick and Delaune, 1976; Mendelssohn, 1978). Under some circumstances, smooth cordgrass will increase growth in response to fertilizer applications of as much as 672 kilograms of nitrogen (N) and 74 kilonewtons of phosphorus (P_2O_5) per hectare per year (Woodhouse, Seneca, and Broome, 1974, 1976). Apparent recovery of applied nitrogen may be as high as 40 to 60 percent in shoot growth alone, a value that compares favorably with upland field crops. The potential for substantial recycling and exporting of nutrients to the estuary exists. The absorption, conversion, and recycling capabilities of marsh plants offer real opportunities for water purification (Woodhill, 1977).

c. Esthetics. Marshes are a visual transition between land and water and a natural feature of the landscape adding form, color, and texture to the shore. Unlike other forms of shore protection, once plants are established there remains no visible evidence that there has been a human effort to reduce erosion as illustrated by Figure 37. In addition, the unique assemblage of birds and mammals which are associated with marshes are of interest and are often subjects of photographic and illustrative art forms. Standard structural methods of shore protection may visually alter the shoreline (Fig. 38), creating a barrier rather than a transition between land and water.

2. Potential Negative Impacts.

a. Public Access. Vegetative stabilization discourages certain recreational activities. Vegetation discourages public access for water-oriented activities such as swimming, wading, and sunbathing. In addition, vegetation discourages fishing from the shore; other shore protection structures often provide a platform for fishing use.

b. Heavy Metal Release. There has been concern expressed that intertidal marshes are a mechanism for releases of potentially toxic, heavy metals to estuarine systems and the ocean. This is a subject of extreme complexity. Gunnison (1978) has recently summarized existing information on mineral cycling in marsh-estuarine ecosystems.

In general, the release of heavy metals is not a major concern for shore stabilization projects unless sediments with high levels of heavy metals are



Figure 37. Vegetative erosion control project (Maryland).



Figure 38. Erosion control structure (Maryland).

used to grade the site prior to planting. In which case, the issue of heavy metal release should be resolved on a case-by-case basis. However, it is also advisable to consider this issue when sizable shore stabilization projects are proposed for areas with highly polluted sediments.

c. Introducing Nuisance Species. Although most coastal marsh species are highly regarded as ecologically beneficial, some are not. Common reed (*Phragmites communis*) in particular has a reputation in this country as a nuisance plant. More literature is available on eradicating common reed than on planting it. It is purported to be of little direct value to wildlife and aggressively crowds out other desirable species. It grows in dense monotypic stands often to a height of more than 3 meters, which can interrupt views of the water and preclude public access.

The introduction of nonnative species may also have negative impacts. Most marsh plants are aggressive colonizers. When introduced to regions where they do not occur naturally, they may spread rapidly in the absence of the diseases and predators which act as biological controls in their native environments. However, in their new environment they may displace species which have ecological or agricultural significance. For these reasons all plants recommended for planting in this report are native in the region for which they have been recommended.

d. Nutrient Pollution. The possible contribution to eutrophication should be considered when the addition of nutrients to any part of an estuary is contemplated. Although there are no data bearing directly on this question, the following are sound reasons to believe that the judicious use of fertilizers in developing marshes for shoreline erosion control is unlikely to contribute significantly to the pollution load of estuaries:

(1) The amount of nitrogen applied in a planting encompassing only a small part of an estuary will be insignificant in comparison with the nitrogen regularly entering that estuary from other sources (agricultural, municipal, and industrial).

(2) Little phosphorus is likely to leave the planted area because of the affinity of marsh sediments for this nutrient. The planting will remove and immobilize phosphorus from the estuary in succeeding years.

(3) Utilization of applied nitrogen by marsh plantings can be quite efficient. Apparent recovery in aboveground growth in the year of application has been as high as 50 percent, comparable to that of most upland crops (Woodhouse, Seneca, and Broome, 1976).

(4) Slow-release materials will contribute even less to the estuary.

(5) Fertilization will usually be a one season, or in rare cases, a two- or three-season event. The resulting marsh will be capable of immobilizing much larger quantities of pollutants every year.

3. Summary.

a. Potential Benefits:

- (1) Marsh ecology - tidal marshes are ecologically valuable.
- (2) Nutrient cycling - tidal marshes have substantial absorptive capacities of potential pollutants.
- (3) Esthetic - tidal marshes are esthetically pleasing.

b. Potential Negative Impact:

- (1) Public access - tidal marshes discourage some water-oriented recreational activities (fishing, swimming, and sunbathing).
- (2) Heavy metal release - tidal marshes may concentrate and export some heavy metals.
- (3) Introducing nuisance species - some tidal marsh plants are considered to have little environmental value.

LITERATURE CITED

- ANDERSON, C.E., "A Review of Structure in Several North Carolina Salt Marsh Plants," *Ecology of Halophytes*, Academic Press, New York, 1974, pp. 303-340.
- BARKO, J.W., and SMART, R.M., "Establishment and Growth of Selected Freshwater and Coastal Marsh Plants in Relation to Characteristics of Dredged Sediments," TR D-77-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Mar. 1977.
- BROOME, S.W., SENECA, E.D., and WOODHOUSE, W.W., Jr., "Effects of Source, Rate, and Placement of Nitrogen and Phosphorus Fertilizers on Growth of *Spartina alterniflora* Transplants in North Carolina," *Estuaries* (in preparation, 1983).
- CAMMEN, L.M., "Microinvertebrate Colonization of *Spartina* Marsh Artificially Established on Dredge Spoil," *Estuarine and Coastal Marine Science*, Vol. 4, No. 4, 1976, pp. 357-372.
- CAMMEN, L.M., SENECA, E.D., and COPELAND, B.J., "Animal Colonization of Salt Marshes Artificially Established on Dredge Spoil," TP 76-7, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., June 1976.
- CARLTON, J.M., "Land-Building and Stabilization by Mangroves," *Environmental Conservation*, Vol. 1, No. 4, 1974, pp. 285-294.
- CASAGRANDE, A., "Classification and Identification of Soils," *Transactions of the American Society of Civil Engineers*, Vol. 113, No. 2351, 1948, pp. 901-930.
- CHABRECK, R.H., "Vegetation, Water, and Soil Characteristics of the Louisiana Coastal Region," Bulletin No. 664, Louisiana Agricultural Experiment Station, Baton Rouge, La. Sept. 1972.
- CHAPMAN, V.J., "Studies in Salt Marsh Ecology: VI-VII, Comparison with the Marshes on the East Coast of North America," *Journal of Ecology*, No. 28, 1940, pp 118-152.
- COOPER, A.W., "Salt Marshes," *Coastal Ecological Systems of the United States*, M.T. Odum, B.J. Copeland, and E.F. McNammon, eds., Vol. I, Institute of Marine Science, University of North Carolina, Chapel Hill, N.C., 1969, pp. 567-611.
- DAI, T.S., HILL, I.K., and SMITH, D.W., "The Role of Vegetation in Stabilizing the Lower Great Lakes Canadian Shoreline," *Journal of Great Lakes Research*, Vol. 3, No. 1-2, Oct. 1977, pp. 46-56.
- DAVIS, J.H., Jr., "The Ecology and Geologic Role of Mangroves in Florida," Publication 517, Vol. 32, No. 16, Carnegie Institute, Washington, D.C., 1940, pp. 307-409.
- DEAN, R.G., "Effects of Vegetation on Shoreline Erosional Processes," unpublished, 1979.

- DODD, J.D., and WEBB, J.W., "Establishment of Vegetation for Shoreline Stabilization in Galveston Bay," MP 6-75, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., Apr. 1975.
- ECKERT, J.W., GILES, M.L., and SMITH, G.M., "Design Concepts for In-Wave Containment Structures for Marsh Habitat Development," TR D-78-31, *Dredge Material Research Program*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., July 1978.
- ENDO, T., and TSURUTA, T., "The Effect of Tree Roots Upon the Shearing Strength of Soil," Annual Report No. 18, Tokyo Forest Experimental Station, Tokyo, Japan, 1969, pp. 168-179.
- FLOYD, K.W., and NEWCOMBE, C.L., "Growth of Intertidal Marsh Plants on Dredge Material Substrates," Appendix K, Inclosure 3, *San Francisco Bay and Estuary Dredge Disposal Study*, San Francisco Bay Marine Research Center, Emeryville, Calif., Feb. 1976.
- GALLAGHER, J.L., PLUMLEY, F.G., and WOLF, P.L., "Underground Biomass Dynamics and Substrate Selective Properties of Atlantic Coastal Marsh Plants," TR D-77-28, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Dec. 1977.
- GARBISCH, E.W., Jr., "Recent and Planned Marsh Establishment Work Throughout the Contiguous United States. A Survey and Basic Guidelines." CR D-77-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Apr. 1977a.
- GARBISCH, E.W., Jr., "Vegetative Stabilization Site Information Forms, Chesapeake Bay," Contract No. DACW72-77-M-0712, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., unpublished, 1977b.
- GARBISCH, E.W., Jr., WOLLER, P.B., and McCALLUM, R.J., "Salt Marsh Establishment and Development," TM-52, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., June 1975.
- GERRISH, W., "Chromosomal Analysis of a Previously Unidentified *Spartina*," unpublished M.S. Thesis, C.W. Post College, Long Island University, New York, 1979.
- GOSSELINK, J.G., "Growth of *S. patens* and *S. alterniflora* as Influenced by Salinity and Source of Nitrogen," Coastal Studies Bulletin No. 5, Louisiana State University, Center for Wetland Resources, Baton Rouge, La., 1970, pp. 97-109.
- GRAY, D.M., "Reinforcement and Stabilization of Soil by Vegetation," *Journal of the Geotechnical Engineering Division*, 100, No. GT6, 1974, pp. 696-699.
- GRAY, D.M., "The Role and Use of Vegetation for the Protection of Backshore Slopes in the Coastal Zone," Technical Report, Department of Civil Engineers, University of Michigan, Ann Arbor, Mich., 1975.
- GREAT LAKES BASIN COMMISSION, "The Role of Vegetation in Shoreline Management, A Guide for Great Lakes Shoreline Property Owners," Great Lakes Basin Commission, Great Lakes, Ill., 1978.

- GUNNISON, D., "Mineral Cycling in Salt Marsh-Estuarine Ecosystems," TR D-78-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Jan. 1978
- HALL, V.L., and LUDWIG, J.D., "Evaluation of Potential Use of Vegetation for Erosion Abatement Along the Great Lakes Shoreline," MP 7-75, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., June 1975.
- HARDISKY, M.H., and REIMOLD, R.J., "Buttermilk Sound Marsh Habitat Development Site, Glynn County, Georgia," Department of Natural Resources, Georgia, 1979.
- HARVEY, H.T., "Growth and Elevational Transplant Studies of *Spartina foliosa* in Dredge Material," Inclosure 2, Appendix B, *San Francisco Bay and Estuary Dredge Disposal Study, Appendix K, Marsh Development*, U.S. Army Engineer District, San Francisco, San Francisco, Calif., Apr. 1976, pp. 109-111.
- HINDE, H.P., "The Vertical Distribution of Salt Marsh Phanerogams in Relation to Tide Levels," *Ecological Monographs*, Vol. 24, 1954, pp. 209-225.
- JEFFERSON, C.A., "Coastal Wetlands of Oregon," G.J. Akins, ed., Oregon Coastal Conservation and Development Commission, Florence, Oreg., Aug. 1973.
- JEFFERSON, C.A., "Plant Communities and Succession in Oregon Coastal Salt Marshes," unpublished Ph.D. Thesis, Oregon State University, Corvallis, Oreg., June 1975.
- JOHNSON, D.S., and YORK, M.H., "The Relation of Plants to Tide Levels," Carnegie Institute, Washington, D.C., 1915.
- KADLEC, J.H., and WENTZ, W.A., "State of the Art Survey and Evaluation of Marsh Plant Establishment Techniques: Induced and Natural," Vol. I, TR D-74-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., 1974.
- KASAPLIGIL, B., "A Synoptic Report on the Morphology and Ecological Anatomy of *Spartina Foliosa* Trin," Inclosure 2, Appendix C, *San Francisco Bay and Estuary Dredge Disposal Study, Appendix K, Marsh Development*, U.S. Army Engineer District, San Francisco, San Francisco, Calif., Apr. 1976, pp. 112-127.
- KNUTSON, P.L., "Development of Intertidal Marshlands Upon Dredged Material in San Francisco Bay," *Proceedings of the Seventh Conference on World Dredging*, 1976, pp. 103-118.
- KNUTSON, P.L., "Planting Guidelines for Marsh Development and Bank Stabilization," CETA 77-3, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., Aug. 1977a.
- KNUTSON, P.L., "Designing for Bank Erosion Control with Vegetation," *Coastal Sediments '77*, American Society of Civil Engineers, 1977b, pp. 716-733 (also Reprint 78-2, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., NTIS A051 571).

- KNUTSON, P.L., et al., "National Survey of Planted Salt Marshes (Vegetative Stabilization and Wave Stress)," *Wetlands, Journal of the Society of Wetland Scientists*, Sept. 1981.
- KNUTSON, P.L., SEELIG, W.N. and INSKEEP, M.R., "Wave Damping in *Spartina alterniflora* Marshes," *Wetlands, Journal of the Society of Wetland Scientists* (in preparation, 1983).
- LEWIS, R.R., and DUNSTAN, F.M., "The Possible Role of *Spartina alterniflora* in Establishment of Mangroves in Florida," *Proceedings of the Second Annual Conference on Restoration of Coastal Vegetation in Florida*, R.R. Lewis, ed., 1975, pp. 82-101.
- LEWIS, R.R., and DUNSTAN, F.M., "Results of Mangrove Planting Experiments on a Spoil Island in Tampa Bay," Tampa Port Authority, Tampa, Fla., 1976.
- MCDONALD, K.B., and BARBOUR, M.G., "Beach and Salt Marsh Vegetation of the North American Pacific Coast," *Ecology of Halophytes*, W.H. Queen and R.T. Reimold, eds., Academic Press, New York, 1974.
- MANBEIAN, T., "The Influence of Soil Moisture Suction, Cyclic Wetting and Drying, and Plant Roots on the Shear Strength of a Cohesive Soil," Ph.D. Thesis, University of California, Berkeley, Calif., 1973.
- MASON, H.L., "Marsh Development Study, Phase One, Preliminary Investigation," Inclosure I, *San Francisco Bay and Estuary Dredge Disposal Study, Appendix K, Marsh Development*, U.S. Army Engineer District, San Francisco, San Francisco, Calif., Apr. 1976.
- MENDELSSOHN, J.A., "The Influence of N Level, Form, and Application Method on Growth Response of *Spartina alterniflora* in North Carolina," *Estuaries* 2, 1979, pp. 106-111.
- MOORING, M.T., COOPER, A.W., and SENECA, E.D., "Seed Germination Response and Evidence for Height Ecophenes in *Spartina alterniflora* from North Carolina," *American Journal of Botany*, Vol. 58, No. 1, Jan. 1971, pp 48-55.
- MORRIS, J.H., and NEWCOMBE, C.L., "Investigations of Marsh Ecosystem Establishment on Fine-Grained Dredge Material at Salt Pond No. 3, South San Francisco Bay, Alameda County, California," U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., 1978.
- NEWCOMBE, C.L., et al., "Bank Erosion Control with Vegetation, San Francisco Bay, California," MR 79-2, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., May 1979.
- PATRICK, W.H., Jr., and DELAUNE, R.D., "Nitrogen and Phosphorus Utilization by *Spartina alterniflora* in a Salt Marsh in Barataria Bay, Louisiana," *Estuarine and Coastal Marine Science*, Vol. 4, 1976, pp. 59-64.
- PATRICK, W.H., Jr., and MAHAPATRA, I.C., "Transformation and Availability to Rice of Nitrogen and Phosphorus in Waterlogged Soils," *Advances in Agronomy*, Vol. 20, 1968, pp. 323-359.
- PESTRONG, R., "San Francisco Bay Tidelands" *California Geology*, Vol. 25, No. 2, Feb. 1972.

- PHILLIPS, W.A., and EASTMAN, F.D., "Riverbank Stabilization in Virginia," *Journal of Soil and Water Conservation*, No. 14, 1959, pp. 257-259.
- PHLEGER, C.F., "Effect of Salinity on Growth of a Salt Marsh Grass," *Ecology*, Vol. 52, 1971, pp. 908-911.
- PRIDE, C.B., and LINGLE, D.E., "Redox Potentials in Soil Environments of Cordgrass, *Spartina foliosa*," Trin, Inclosure 2, Appendix A, *San Francisco Bay and Estuary Dredge Disposal Study, Appendix K, Marsh Development*, U.S. Army Engineer District, San Francisco, San Francisco, Calif., Apr. 1976, pp. 85-101.
- PULVER, T.R., "Transplant Techniques for Sapling Mangrove Trees, *Rhizophora Mangle*, *Laguncularia Racemosa*, and *Avicennia Germinans* in Florida," No. 22, Florida Department of Natural Resources, Marine Research Laboratory, St. Petersburg, Fla., Nov. 1976.
- PURER, E.A., "Plant Ecology of the Coastal Salt Marshlands of San Diego County, California," *Ecological Monographs*, Vol. 12, 1942, pp. 81-111.
- REDFIELD, A.C., "Development of a New England Salt Marsh," *Ecological Monographs*, Vol. 42, No. 2, 1972, pp. 201-237.
- REIMOLD, R.J., and LINTHURST, R.A., "Primary Productivity of Minor Marsh Plant in Delaware, Georgia, and Maine," TR D-77-36, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Nov. 1977.
- ROWNTREE, R.A., "Morphological Change in a California Estuary: Sedimentation and Marsh Invasion at Bolinas Lagoon," unpublished Ph.D. Dissertation, University of California, Berkeley, Calif., 1973.
- SAVAGE, T., "Florida Mangroves as Shoreline Stabilizer," No. 19, Florida Department of Natural Resources, Marine Research Laboratory, St. Petersburg, Fla., Aug. 1972.
- SENECA, F.D., "Germination and Seedling Response of Atlantic and Gulf Coasts Populations of *Spartina Alterniflora*," *American Journal of Botany*, Vol. 61, No. 9, 1974, pp. 947-956.
- SHARP, W.C., and VADEN J., "Ten-Year Report on Sloping Techniques Used to Stabilize Eroding Tidal River Banks," *Shore and Beach*, Vol. 38, Apr. 1970, pp. 31-35.
- SHARP, W.C., BELCHER, C.R., and OYLER, J., "Vegetation for Tidal Stabilization in the Mid-Atlantic States," U.S. Department of Agriculture, Soil Conservation Service, Broomall, Pa., 1981.
- SILANDER, J.A., "Microevolution and Clone Structure in *Spartina Patens*," *Science*, Vol. 203, Feb. 1979.
- SMART, R.M., and BARKO, J.W., "Influence of Sediment Salinity and Nutrients on the Physiological Ecology of Selected Salt Marsh Plants," *Estuarine and Coastal Marine Science*, No. 7, 1978, pp. 487-495.
- SORENSEN, R.M., "Water Waves Produced by Ships," *Journal of the Waterways and Harbors Division*, Vol. 99, No. WW2, May 1973, pp. 245-256.

- SORENSEN, R.M., "Investigation of Ship-Generated Waves," *Journal of the Waterways and Harbors Division*, Vol. 93, No. WW1, Feb. 1967, pp. 85-99.
- TEAL, J.M., and KANWISHER, J.W., "Gas Transport in the Marsh Grass, *Spartina alterniflora*," *Journal of Experimental Botany*, Vol. 17, No. 51, May 1966, pp. 355-361.
- TEAS, H.J., "Ecology and Restoration of Mangrove Shorelines in Florida," *Environmental Conservation*, Vol. 42, No. 1, 1977, pp. 51-58.
- TEAS, H.J., JERGENS, W.H., and KIMBALL, M.C., "Plantings of Red Mangrove (*Rhizophora mangle*) in Charlotte and St. Lucie Counties, Florida," *Proceedings of the Second Annual Conference on the Restoration of Coastal Vegetation in Florida*, R.R. Lewis, ed., 1975, pp. 132-161.
- TERNYIK, W.E., "Pilot Propagation of Vascular Plants on Miller Sands Habitat and Marsh Development Site, Columbia River, Oregon," IWD D-77-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Mar. 1977.
- TERNYIK, W.E., "Habitat Development Field Investigations, Miller Sands Marsh and Upland Habitat Development Site, Columbia River, Oregon," Appendix D: *Propagation of Vascular Plants on Dredged Material*, TR D-77-35, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., 1978.
- U.S. ARMY, CORPS OF ENGINEERS, COASTAL ENGINEERING RESEARCH CENTER, *Shore Protection Manual*, 3d ed., Vols. I, II, and III, Stock No. 008-022-00113-1, U.S. Government Printing Office, Washington, D.C., 1977, pp. 1,262.
- U.S. ARMY, CORPS OF ENGINEERS, COASTAL ENGINEERING RESEARCH CENTER, *Shore Protection Manual*, 4th ed., U.S. Government Printing Office, Washington, D.C. (in preparation, 1983).
- U.S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, "The Unified Soil Classification System," Vol I, Vicksburg, Miss., 1953.
- U.S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, "Wetland Habitat Development with Dredged Material: Engineering and Plant Propagation," TR DS-78-16, Vicksburg, Miss., 1978.
- U.S. ARMY ENGINEER DISTRICT, SAN FRANCISCO, "San Francisco Bay and Estuary Dredge Disposal Study," Appendix K, *Marsh Development*, San Francisco, Calif., Apr. 1976.
- VALIELA, I., and TEAL, J.M., "Nutrient Limitation in Salt Marsh Vegetation," *Ecology of Halophytes*, R.J. Reimold and W.H. Queen, eds., Academic Press, New York, 1974, pp 547-564.
- WASEL, Y., *Biology of Halophytes*, Academic Press, New York, 1972.
- WARD, E., "Phragmites Management," *Transactions of the North American Wild. Conference*, No. 7, 1942, pp. 294-298.
- WAYNE, C.J., "Sea and Marshgrasses: Their Effects on Wave Energy and Near-Shore Transport," M.S. Thesis, Florida State University, Tallahassee, Fla., 1975.

WEBB, J.W., and DODD, J.D., "Vegetation Establishment and Shoreline Stabilization, Galveston Bay, Texas," TP 76-13, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., Aug. 1976.

WEBB, J.W., and DODD, J.D., "Shoreline Plant Establishment and Use of a Wave-Stilling Device," MR 78-1, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., Jan. 1978.

WEBB, J.W., et al., "Habitat Development Field Investigations, Bolivar Peninsula Marsh and Upland Habitat Development Site, Galveston, Texas," Appendix D: *Propagation of Vascular Plants and Postpropagation Monitoring of Botanical, Soil, Aquatic Biota and Wildlife Resources*, TR D-78-15, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., June 1978.

WEIGEL, R.L., *Oceanographic Engineering*, 2d ed., Prentice-Hall, Inc. Englewood Cliffs, N.J., 1965.

WILLIAMS, R.B., and MURDOCK, M.B., "The Potential Importance of *Spartina alterniflora* in Conveying Zinc, Manganese, and Iron into Estuarine Food Chains," *Proceedings of the Second National Symposium on Radioecology*, 1969.

WONG, G., "Oxygen Transport in *Spartina foliosa* Trin., "Inclosure 2, Appendix E, *San Francisco Bay and Estuary Dredge Disposal Study*, Appendix K, *Marsh Development*, U.S. Army Engineer District, San Francisco, San Francisco, Calif., Apr. 1976, pp. 132-136.

WOODHILL, G.M., "Recycling Sewage Through Plant Communities," *American Scientist*, Vol. 65, No. 5, Sept. 1977, pp. 556-562.

WOODHOUSE, W.W., Jr., "Building Salt Marshes Along the Coasts of the Continental United States," SR 4, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., May 1979.

WOODHOUSE, W.W., Jr., SENECA, E.D., and BROOME, S.W., "Marsh Building with Dredge Spoil in North Carolina," Bulletin 445, Agricultural Experiment Station, North Carolina State University, Raleigh, N.C., July 1972.

WOODHOUSE, W.W., Jr., SENECA, E.D., and BROOME, S.W., "Propagation of *Spartina alterniflora* for Substrate Stabilization and Salt Marsh Development," TM-46, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., Aug., 1974.

WOODHOUSE, W.W., Jr., SENECA, E.D., and BROOME, S.W., "Propagation and Use of *Spartina alterniflora* for Shoreline Erosion Abatement," TR 76-2, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., Aug. 1976.

Knutson, Paul L.

Shore stabilization with salt marsh vegetation / by Paul L. Knutson and W.W. Woodhouse, Jr.--Port Belvoir, Va. : U.S. Army Coastal Engineering Research Center, Springfield, Va. : available from NTIS, 1983. [95] p. : ill. ; 28 cm.--(Special report / Coastal Engineering Research Center ; no. 9)

Cover title.

"January 1983."

Report provides guidelines on using coastal marsh vegetation as a shore erosion control measure in relatively sheltered U.S. shorelines such as those found on bays, sounds, and estuaries. Criteria are provided on (1) determining site suitability, (2) selecting plant materials, (3) planting procedures and specifications, (4) estimating project costs, and (5) assessing impact.

I. Marsh vegetation. 2. Shore stabilization. 3. Erosion control. I. Title. II. Woodhouse, W.W., Jr. III. Coastal Engineering Research Center (U.S.). IV. Series: Special report (Coastal Engineering Research Center (U.S.)); no. 9.

.U581sr

no. 9

627

TC203

Knutson, Paul L.

Shore stabilization with salt marsh vegetation / by Paul L. Knutson and W.W. Woodhouse, Jr.--Port Belvoir, Va. : U.S. Army Coastal Engineering Research Center, Springfield, Va. : available from NTIS, 1983. [95] p. : ill. ; 28 cm.--(Special report / Coastal Engineering Research Center ; no. 9)

Cover title.

"January 1983."

Report provides guidelines on using coastal marsh vegetation as a shore erosion control measure in relatively sheltered U.S. shorelines such as those found on bays, sounds, and estuaries. Criteria are provided on (1) determining site suitability, (2) selecting plant materials, (3) planting procedures and specifications, (4) estimating project costs, and (5) assessing impact.

I. Marsh vegetation. 2. Shore stabilization. 3. Erosion control. I. Title. II. Woodhouse, W.W., Jr. III. Coastal Engineering Research Center (U.S.). IV. Series: Special report (Coastal Engineering Research Center (U.S.)); no. 9.

.U581sr

no. 9

627

TC203

Knutson, Paul L.

Shore stabilization with salt marsh vegetation / by Paul L. Knutson and W.W. Woodhouse, Jr.--Port Belvoir, Va. : U.S. Army Coastal Engineering Research Center, Springfield, Va. : available from NTIS, 1983. [95] p. : ill. ; 28 cm.--(Special report / Coastal Engineering Research Center ; no. 9)

Cover title.

"January 1983."

Report provides guidelines on using coastal marsh vegetation as a shore erosion control measure in relatively sheltered U.S. shorelines such as those found on bays, sounds, and estuaries. Criteria are provided on (1) determining site suitability, (2) selecting plant materials, (3) planting procedures and specifications, (4) estimating project costs, and (5) assessing impact.

I. Marsh vegetation. 2. Shore stabilization. 3. Erosion control. I. Title. II. Woodhouse, W.W., Jr. III. Coastal Engineering Research Center (U.S.). IV. Series: Special report (Coastal Engineering Research Center (U.S.)); no. 9.

.U581sr

no. 9

627

TC203

Knutson, Paul L.

Shore stabilization with salt marsh vegetation / by Paul L. Knutson and W.W. Woodhouse, Jr.--Port Belvoir, Va. : U.S. Army Coastal Engineering Research Center, Springfield, Va. : available from NTIS, 1983. [95] p. : ill. ; 28 cm.--(Special report / Coastal Engineering Research Center ; no. 9)

Cover title.

"January 1983."

Report provides guidelines on using coastal marsh vegetation as a shore erosion control measure in relatively sheltered U.S. shorelines such as those found on bays, sounds, and estuaries. Criteria are provided on (1) determining site suitability, (2) selecting plant materials, (3) planting procedures and specifications, (4) estimating project costs, and (5) assessing impact.

I. Marsh vegetation. 2. Shore stabilization. 3. Erosion control. I. Title. II. Woodhouse, W.W., Jr. III. Coastal Engineering Research Center (U.S.). IV. Series: Special report (Coastal Engineering Research Center (U.S.)); no. 9.

.U581sr

no. 9

627

TC203